

The structural, serviceability and durability performance of variable density concrete panels

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Abstract

Conventional concrete is a poor insulating material but has good thermal mass, while lightweight concrete provides good insulation at the price of thermal mass. Precast concrete wall systems have not been widely used in residential homes due to poor thermal and acoustic performance, despite being high quality products that are easy to construct. The variable density concrete panel was designed to combine good thermal storage, insulation and high quality precast concrete. It is produced from a single concrete mix which is vibrated to get a lightweight top layer and a normal/heavyweight bottom layer. The lightweight layer is the wall exterior, having low thermal conductivity providing good thermal insulation while the normal/heavyweight layer is the dense wall interior, having high specific heat to provide good thermal mass and sufficient strength for construction handling and to withstand service loads.

The intention of this research was to estimate the hardened performance; that is the structural, serviceability and durability performance of the variable density concrete panel. Further developments to the mix design were made where the fresh properties were measured and thermal performance estimated on hardened specimens. Most of the major technical concerns were proved not being as severe as first thought, making the production of variable density concrete panels promising.

To ensure that the variable density concrete would stratify, the concrete mix had to have defined fresh properties. Defined rheological ranges gave a good indication of the stratification potential, but the degree of stratification was also found to be dependent on the intensity and time of vibration. Slump flow had to be within a certain range to achieve good stratification but this alone did not guarantee stratification.

Variable density concrete was found to have adequate strength capacity both in axial compression and in tension for likely service loads but the strength required to withstand handling loads at early ages was not assessed. The strength of the variable density concrete was found to be affected by several factors such as; degree of stratification, relative strength and thickness of the layers, curing environment and amount of defects. As the stratification of the concrete increased the thermal insulation improved whereas the strength decreased.

Warping was found not to significantly affect the serviceability of panels despite differential shrinkage within the element. The amount of warping was mainly related to the degree of stratification. Warping decreased with better stratification as more stress and strain was relieved in the lightweight layer. The lightweight concrete was significantly weaker as well as being less stiff than the structural concrete and therefore creeps to follow the structural concrete.

The thermal properties aimed for were generally not reached, but these mixes were not designed to optimise the thermal performance and were tested before the concrete was fully dried. This increased thermal conductivity and therefore reduced the measured R-values.

Stratified concrete had good absorption resistance, poor permeability properties and was highly porous. If the concrete was over-vibrated it tended to have a rough surface finish that would require a coating. Delamination of the panels was not assessed in this research but is a likely mode of failure.

Acknowledgements

This research was carried out in the Department of Civil Engineering at the University of Canterbury and was supervised by Dr. J.R. Mackechnie. Without his contribution and knowledge it would not have been possible to carry through this research.

1 Introduction

Conventional concrete is a poor insulating material but has good thermal mass while lightweight concrete provides good insulation at the price of thermal mass. Precast concrete walls systems have not been widely used in residential homes due to poor thermal and acoustic performance. Precast concrete can however provide high quality products and are easy to construct. Several concrete wall systems are currently manufactured with improved insulation values using various insulating mediums, such as polystyrene sheeting attached to either the interior or exterior face, or located within the panel (“sandwich panel”). These products do however prevent the full thermal mass of concrete being utilized.¹ Insulating concrete forms are not ideal in terms of energy efficiency, cost and labour requirements.

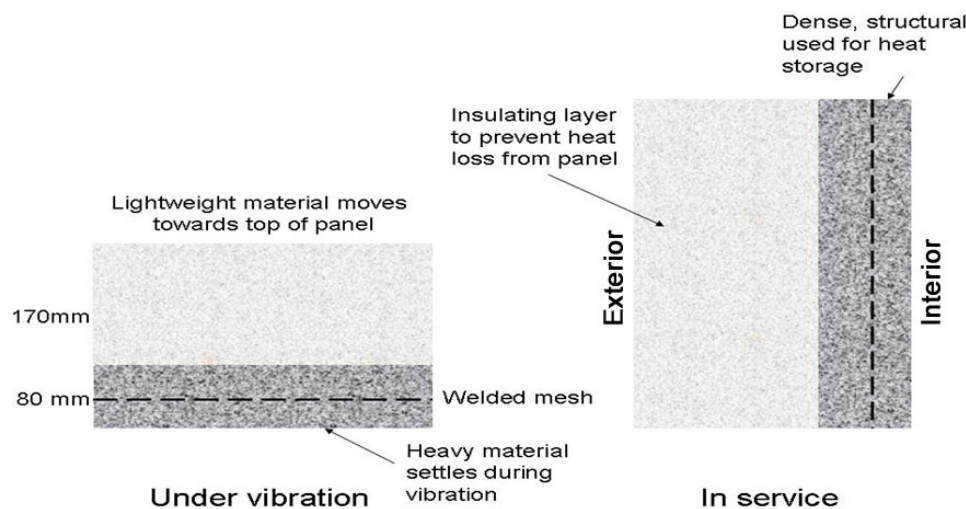


Figure 1.1 – Illustration of variable density concrete panel²

Trying to combine good thermal storage, insulation and high quality precast concrete Bellamy and McSaveney³ proposed the concept of the variable density concrete panel. The variable density concrete panel, Figure 1.1, is produced from a single concrete mix which is vibrated to achieve:

- Lightweight insulating top (outside) layer with low thermal conductivity providing good thermal insulation
- Heavy/normal weight material, dense bottom (inside) layer with high specific heat to provide thermal mass and sufficient strength for construction handling and to withstand service loads

Stratified concrete was achieved by using aggregates of different densities within a moderately viscous paste that was stratified to get different layers within the panel from a single batch of

¹ CCANZ, Cement & Concrete Association of New Zealand. 2007.

² Mackechnie, J.R.; Park, Y.S.; Sævarsdóttir, T & Bellamy, L. 2007

³ Bellamy, L.A. & McSaveney, L.G. 2003

concrete. On top of the lightweight layer, a wearing or surface coat will be placed to protect the lightweight concrete and to make a better appearance of the panel (not shown in Figure 1.1).

To ensure controlled segregation of the concrete, the mix required careful formation and selection of materials. The following materials were used in this initial work on the variable density panels:

- Heavyweight aggregates – slag granules, greywacke sandstone
- Lightweight aggregates – expanded glass beads, perlite, pumice
- Binders – Portland cement, inorganic polymers cement made with fly ash and/or slag

The mix design and some of the tests of the inorganic polymer concrete was performed by others at the University of Canterbury.⁴ After some initial trials, technical objectives for the variable density panels were developed and are listed in Table 1.1.

Table 1.1 – Technical objectives for the variable density concrete panel⁵

Material Property	Top Layer	Bottom Layer
Thickness [mm]	170	80
Density [kg/m^3]	1000	2250
Compressive Strength [MPa]	2-5	25-35
Thermal Conductivity [W/mK]	<0.25	1.00-1.25
Specific Heat [MJ/m^3K]	0.75-1.25	2.00-3.00
R-value panel [m^2K/W]	0.8-1.0	

The thickness of the top and bottom layer was estimated to get the optimum thermal performance from the panel; roughly two thirds of the depth should be lightweight insulating concrete and the remaining third normal/heavy weight thermal storage concrete. As well as providing thermal storage, the bottom layer had to be thick enough to provide reasonable cover and bond to a light welded mesh within the layer.⁶ As mentioned before the bottom layer also had to be thick enough to provide sufficient strength for service loads and handling.

The intention of this research was to estimate the hardened performance of the variable density concrete panels, developed within the Future Building Systems research programme. Previous research had proved that controlled stratification of concrete is possible, producing a lightweight top layer and a structural bottom layer.⁷ The thermal performance of the material had also been shown to be excellent, with thermal conductivity values of as low as $0.2W/mK$ and R-values of above 0.6.

Development of this building concept had to move beyond mix design and rheological characterisation to assess the hardened performance of the stratified concrete. The structural performance, serviceability (e.g. warping and cracking) and durability had to be assessed, modelled or measured experimentally. Initial aims of this research, assessed here were:

- Assessing the structural performance of reinforced concrete panels in the laboratory under typical loads likely during handling and after installation

⁴ Mackechnie, J.R. 2007

⁵ Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007

⁶ Mackechnie, J.R.; Park, Y.S.; Sævarsdóttir, T & Bellamy, L. 2007

⁷ Park, Y.S. 2006

- Model and measure the serviceability of typical panels in terms of warping, cracking and shrinkage
- Assess the durability performance of the material, using tests such as permeability and sorptivity
- Cast and monitor trial walling systems on site exposed to outdoor weather conditions (mainly to assess serviceability of system)

On top of these initial aims some further mix design had to be carried out to be able to investigate the structural, serviceability and durability performance of the variable density concrete.

There were many aspects that needed investigation as the variable density concrete is a new concept. This dissertation is therefore extensive but its structure can be described as follows:

Literature Survey (Chapter 2)

As the variable density concrete panel is a new concept, there are many aspects that need to be considered. The literature briefly describes certain properties of concrete, such as; fresh properties, hardened properties, serviceability, durability and thermal properties as well as a description of lightweight and inorganic polymer cement concrete. Following aspects were described further as expected to have huge impact on the design of the panels; drying shrinkage, creep, warping or curling, segregation and lightweight concrete.

Materials and Mix Design (Chapter 3)

To ensure controlled segregation or stratification of the concrete as well as fulfilling the initial technical requirements, concrete mixes required careful formation and selection of materials. Without having an adequate concrete mix design, the production of stratified concrete was not possible. The materials used and the mix design procedure is therefore described.

Methodology (Chapter 4)

Test methods for basic testing of concrete are well known and standardised in concrete technology textbooks. Due to the specialised nature of this research, further test procedures were developed or adopted from elsewhere. These test methods are described in this part of the dissertation.

Experimental results (Chapters 5-10)

The following chapters discuss the experimental results:

- **Chapter 5** is dedicated to **fresh properties** of concrete including rheological properties, slump flow and stratification under vibration. The concrete mix had to stratify during moderate levels of vibration, but remain fairly homogenous during mixing and handling. The segregation had to be controlled and was assessed in the fresh and hardened state. In this chapter the robustness of the mix is also briefly discussed as the mix has to be able to tolerate minor variations in batching, casting and compaction.
- **Chapter 6** gives details of **hardened properties**, particularly compressive and flexural strength of concrete panels made with stratified concrete. The effect of stratification on the structural performance of concrete is also discussed.
- **Chapter 7** covers the **serviceability performance** of variable density panels as it discusses the issue of shrinkage and warping or curling of the variable density concrete

- **Chapter 8** discusses the **thermal properties** of the stratified concrete. The variable density panels were not designed optimizing thermal performance but it was nevertheless measured as one of the key factors of variable density panels
- **Chapter 9** discusses the **durability performance**, as the materials used need to be sufficiently durable and serviceable to provide satisfactory long-term service of the panels.

A summary of the results and potential for variable density concrete are addressed in chapter 10.

1.1 References

- Bellamy, L.A. & McSaveney, L.G. 2003. “*FRST – Future Building Systems Research Proposal*”, University of Canterbury, Christchurch, New Zealand.
- CCANZ, Cement & Concrete Association of New Zealand. 2007, 20th of January. *Residential Precast Concrete Systems*. Web site: <http://www.cca.org.nz>.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Mackechnie, J.R.; Park, Y.S.; Saevarsdottir, T & Bellamy, L. 2007. *Variable Density Precast Concrete Panel Development*. Unpublished paper. University of Canterbury, New Zealand.
- Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007. “Stratified Precast Concrete Panels for Buildings.” *Concrete Plant International*, July 2007.
- Park, Y.S. 2006. Unpublished laboratory findings. University of Canterbury, Christchurch, New Zealand.

2 Literature Survey

Concrete is a complex composite material where aggregates are dispersed particles in a multiphase matrix of cement paste. Concrete is produced and its properties determined by controlling the following performance parameters:

- Fresh properties such as workability, rheology and segregation
- Hardened properties including strength, modulus of elasticity, drying shrinkage and creep
- Serviceability where warping and delamination are of most concern
- Durability including corrosion of reinforcing steel and alkali silica reaction
- Thermal properties of concrete

2.1 Fresh properties

It is vital that consistency of concrete mixes are controlled such that it can be transported, placed, compacted and finished sufficiently easily and without segregation, since the strength and other properties of concrete are highly affected by the degree of its compaction and the homogeneity of the material.

2.1.1 *Workability*

Workable concrete can be readily compacted. Workability is defined as the property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished. Workability suitable for mass concrete is not necessarily sufficient for confined or heavily reinforced sections. Workability of concrete mainly depends on:¹

- The **water content** – increased water content increases the workability. Excessive water is not good however since it leads to increased bleeding and/or segregation of aggregates resulting in reduced quality of the concrete
- The **air content** – increased air increases the workability. Entrained air reduces the strength of the concrete but decreases the damage of freeze thaw action if used correctly
- The **aggregate** – the size, grading, shape and texture of aggregates greatly affect the workability with bigger, crushed badly graded aggregate decreasing the workability
- The **cementitious content** – when increasing the cement content without increasing the water the workability is reduced
- **Age** – as the concrete gets older and further into the process of hydrating it loses its workability as it stiffens
- **Chemical admixtures** – adding chemical admixtures such as superplasticizers and air entraining agents increases the workability of concrete

¹ Neville, A.M. 1995:184-9

2.1.2 Rheology

Rheology is the science of the deformation and flow of matter and involves stress, strain, rate of strain and time. Cement-based materials show solid and fluid-like behaviour, approximated with the Bingham model where the shear stress is related to the yield stress, the product of plastic viscosity and shear rate.² These properties are defined as follows³:

- Yield shear stress is caused by inter-particle forces within concrete such that the material appears stiff until these links are broken by shear
- Plastic viscosity is the resistance to flow once the yield stress has been exceeded
- Shear rate is a measure of the rate of strain within the material during testing and should replicate likely levels during placing and compaction

Pastes composed of cement and water have low yield shear stress ($<100\text{N/m}^2$), as the amount of aggregate increases the yield stress and plastic viscosity increases, due to greater interparticle contact and surface interlocking. Mortars and flowing concrete have therefore moderate yield stress values ($100\text{-}400\text{N/m}^2$) while structural concrete has high yield stress ($500\text{-}2000\text{N/m}^2$). In contrast, the yield stress and plastic viscosity of cement paste increases as the cement gets finer. This reflects the dominance of the water-cement interface in this system, Figure 2.1.

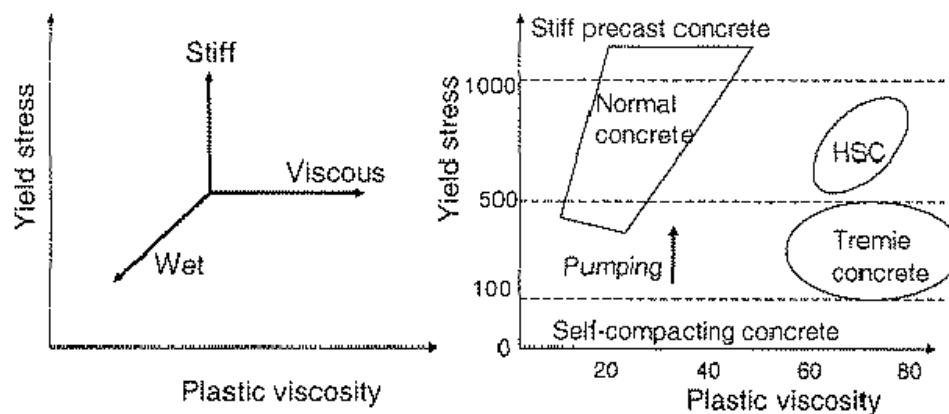


Figure 2.1 – Rheology of concrete⁴

While water reduces and cement increases both the yield stress and the plastic viscosity, different admixtures have different effect on concrete rheology:

- Air reduces the plastic viscosity without affecting the yield stress significantly
- Super-plasticiser significantly reduces the yield stress
- Viscosity modifying agent increases the plastic viscosity

Vibration removes the yield stress of fresh concrete, which then flows under its own weight and allows entrapped air to be released.⁵

² Mackechnie, J.R. 2006

³ Banfill, PFG. 2003

⁴ Mackechnie, J.R. 2006

⁵ Mackechnie, J.R. 2006

2.1.3 Segregation

Segregation is defined as separation of constituents of a heterogeneous mixture so that their distribution is no longer uniform. Concrete consists of materials having various densities varying between 1000kg/m^3 density of water to 3200kg/m^3 density of cement, for conventional normalweight concrete. This range is wider when mixing lightweight concrete, as lightweight aggregates are usually lighter than water. Gravity quickly becomes the enemy of homogeneity having a mixture of relative light and heavy materials.⁶ Different size and specific gravities of particles in concrete mix are therefore the primary causes of segregation within concrete. In concrete there are mainly two forms of segregation or movement of coarse particles:⁷

- Coarser particles separate out since they tend to travel further along a slope or settle more than finer particles
- The grout separates from the mix when the mix is too wet

The development of self compacting concretes has increased the awareness of segregation within concrete. Concrete with good segregation resistance has a distribution of aggregates particles in the concrete relatively equivalent at all locations and at all levels, that is the concrete should not segregate in vertical and horizontal directions. Poor segregation resistance can cause various problems in a concrete member, such as poor deformability and blocking around reinforcement.⁸

By careful handling and suitable grading, the segregation can be controlled⁹ but Popovics¹⁰ has listed factors that contribute to increased segregation:

- Proportion and size of larger particle size (over 25mm) in the concrete mix
- High specific gravity of the coarse aggregate, compared to that of the fine aggregate
- Decreased amount of fines, that is sand and/or cement
- Changes in the particle shape away from smooth, well rounded particles to odd shaped rough particles
- Mixes that are either too wet or too dry

In fresh normalweight concrete the start of settlement of coarse aggregate particles depends on:¹¹

- The yield stress of the mortar
- The density difference between the aggregate particles and the mortar
- The size of the coarse aggregate

Once movement occurs, the velocity of the settlement is affected by:¹²

- The plastic viscosity of the mortar
- The density difference between the coarse aggregate particle and the mortar
- The size of the coarse aggregate

⁶ Roussel, N. 2006

⁷ Neville, A.M. 1995:204-5

⁸ Bui, V.K.; Montgomery, D.; Hinczak, I. & Turner, K. 2002

⁹ Neville, A.M. 1995:204-5

¹⁰ Popovics, S. 1973

¹¹ Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

¹² Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

Reduced yield stress and plastic viscosity of concrete therefore increases the risk of segregation, but improves the workability of fresh concrete from a flow perspective. When designing a concrete mix a compromise must be made to achieve required workability and stability of the concrete.¹³

When the workability of fresh concrete is not appropriate, lightweight and normal/heavyweight aggregates segregate in opposite directions but the physical phenomena are the same:¹⁴

- Lightweight aggregates often have lower particle densities than the mortar matrix in the concrete, causing upward movement of the coarse aggregates
- Normal/heavyweight aggregates have higher particle densities than the mortar matrix in the concrete, causing downward movement of the coarse aggregate as they sink to bottom

By using simple physics it was possible to stratify fresh concrete made with lightweight and heavyweight aggregates in the variable density concrete.

2.2 Hardened properties

2.2.1 *Strength*

Concrete has relatively high compressive strength and low tensile strength, but the tensile strength is only about 10% of the compression strength. At very low compression strengths, $\sim 2\text{MPa}$, the tensile strength can though be as high as 30% of the compression strength. As a result, concrete always fails from tensile stresses even when it is loaded in compression. In practice, concrete is most often constructed with the addition of steel or fiber reinforcement to take up tensile stresses.¹⁵

Using the water/binder ratio to determine the strength has been criticized as not being sufficiently fundamental. In practice however this is still the largest single factor influencing the strength of fully compacted concrete. The strength developed by a workable, properly placed mixture of given cement, acceptable aggregates and water (under the same mixing, curing and testing conditions) is influenced by:¹⁶

- Ratio of cement to mixing water
- Ratio of cement to aggregate
- Grading, maximum size, surface texture, shape, strength and stiffness of aggregate particles

Since the strength of concrete results from:¹⁷

- The strength of the mortar
- The bond between the mortar and the coarse aggregate
- The strength of the coarse aggregate particle (its ability to resist stresses applied to it)

¹³ Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

¹⁴ Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

¹⁵ Neville, A.M. 1995:269-317

¹⁶ Neville, A.M. 1995:269-317

¹⁷ Neville, A.M. 1995:269-317

Using round aggregates reduces the strength of concrete as the interlock between the particles is reduced compared to using coarse aggregate.

Strength is not an intrinsic material property of the concrete. Strength values are sensitive to various factors associated with the manner of their determination, the compression strength of a concrete cylinder is generally higher than that of a companion cube (same mix, degree of compaction, curing history, testing machine and loading rate) under routine test conditions. The cylindrical compression strength of conventional concrete for residential houses in New Zealand is usually between 17.5 and 30MPa.¹⁸

2.2.2 Modulus of elasticity

Concrete is a composite material, a three dimensional combination of two or more distinct materials with a definite interface separating the components. The modulus of elasticity of concrete is a function of the modulus of elasticity of the aggregates, the cement matrix and their relative proportions, Figure 2.2. The relationship between the modulus of elasticity of the concrete materials varies as the modulus of elasticity of the aggregate changes.¹⁹

- In **ordinary normalweight concrete** – the modulus of elasticity of the cement paste is generally much lower than the modulus of elasticity of the aggregates particles
- In **high performance concrete** – the modulus of elasticity of the hydrated cement paste is much higher than in ordinary concrete, decreasing the difference between the modulus of elasticity of the paste and the aggregate
- In **lightweight aggregate concrete** – the modulus of elasticity of the aggregate is much lower than of normal weight aggregate, the difference between the modulus of elasticity of the lightweight aggregate and of the hydrated cement paste is small

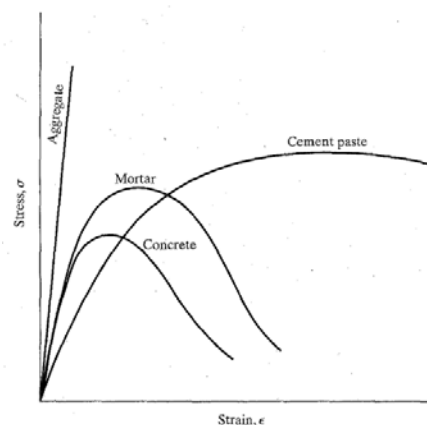


Figure 2.2 - Stress-strain curve for normalweight concrete and its components²⁰

Concrete is a nonlinear inelastic material in both tension and compression. The term modulus of elasticity must therefore be applied with some caution, since it does not represent a single value as it does for a linear elastic material.

¹⁸ CCANZ, 2006

¹⁹ Neville, A.M. 1995:703

²⁰ Mindess, S.; Young, J. F.; Darwin, D. 2003: 304

The chord modulus is most frequently used to determine the elastic modulus, but the chord modulus is the slope of a line drawn between two points on the stress-strain curve. The initial tangent modulus typically corresponds to the slope of the curve at a strain of 5×10^{-5} , which is also used as a lower limit for the chord modulus. The upper limit is usually set at 40% of the compression strength as the chord modulus will underestimate the additional strain that occurs when stress in excess of 40% of the compression strength is imposed on the concrete.²¹

2.2.3 *Drying Shrinkage*

Shrinkage is caused by a volume change in the paste which the aggregates try to restrain and is divided into drying and autogenous shrinkage. Drying shrinkage of hardened concrete is the strain caused in the concrete by its loss of water or shrinkage resulting from loss of moisture. Autogenous shrinkage is when the concrete self-desiccates during hydration or volume change produced by the continued hydration of cement, exclusive of the effects of applied load and change in either thermal conditions or moisture content.²² Inadequate allowance for the effects of drying shrinkage in design and construction of concrete can cause cracking or warping of structural elements due to restraints present during construction.²³

Shrinkage of concrete is mainly dependent on:^{24 25}

- Paste parameters:
 - Porosity (water to binder ratio and degree of hydration)
 - Age of the paste (water to binder ratio and degree of hydration)
 - Curing temperature
 - Cement composition
 - Moisture content
 - Admixtures
- Concrete parameters:
 - Aggregate stiffness
 - Aggregate content (cement content)
 - Volume-surface ratio
 - Thickness
 - Modulus of elasticity of aggregate used
 - Water content in the aggregate
- Environmental parameters
 - Relative humidity
 - Rate of drying
 - Time of drying

As the maximum aggregate size increases the drying shrinkage stresses increases at the cement paste-aggregate interface. Higher internal stresses lead to increased amount of cracking in the interfacial region. Anyhow, lightweight aggregates with a large proportion of fine material, smaller than $75\mu\text{m}$, have a higher shrinkage as the fines lead to a larger void content. Lightweight

²¹ Mindess, S.; Young, J. F.; Darwin, D. 2003: 306-8

²² ACI 116R. 2000

²³ Mindess, S.; Young, J.F. & Darwin, D. 2003:418-419

²⁴ Mindess, S.; Young, J.F. & Darwin, D. 2003:420

²⁵ Zhang, M.H.; Li, L. & Paramasivam, P., 2005:86

aggregates are generally dimensionally stable with low modulus of elasticity, which offers less restraint to the potential shrinkage. Lightweight aggregate concretes are therefore expected to have higher shrinkage than normalweight aggregate concretes.^{26 27} With increased aggregate content the relative shrinkage is decreased, Figure 2.3. When increasing the aggregate content more restraint is provided to volume changes in the paste and the relative amount of paste is decreased.

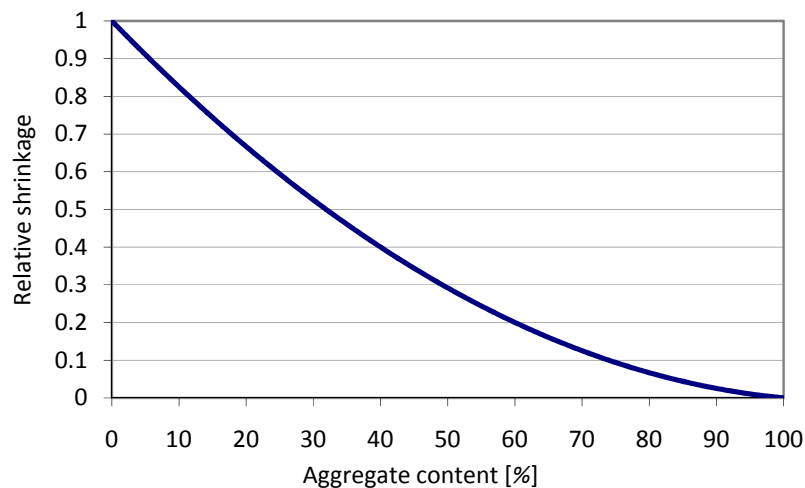


Figure 2.3 – Decreased drying shrinkage with higher aggregate content²⁸

The size and shape of a concrete specimen as well as the length of the diffusion path has a major impact on the rate of moisture loss and therefore the rate and magnitude of drying shrinkage. The rate of moisture loss depends therefore on the total surface area and the average length of the diffusion path. The smaller the initial cross section the faster the initial rate of shrinkage and the lower the magnitude of shrinkage at later times. On the other hand, as the surface areas are reduced, the lower rates of early shrinkage extrapolate to large ultimate shrinkage.

There is no public agreement on the difference in shrinkage between light-, normal- and heavyweight aggregate concrete. Lightweight aggregate concrete is believed to have 5-40% higher initial drying shrinkage than ordinary concrete and even higher total shrinkage.²⁹ This has been proved wrong in some cases, where low shrinkage lightweight concrete has been proved to have lower shrinkage than conventional concrete, as discussed here below. Lightweight aggregates have lower elastic modulus than normalweight aggregates and are therefore less restraint to time-dependent deformations such as drying shrinkage and creep, Figure 2.4.³⁰

²⁶ Mindess, S.; Young, J.F. & Darwin, D. 2003:427

²⁷ Neville, A.M. 1995:434

²⁸ Mindess, S.; Young, J.F. & Darwin, D. 2003:428

²⁹ Neville, A.M. 1995:705

³⁰ Mindess, S.; Young, J.F. & Darwin, D. 2003:551

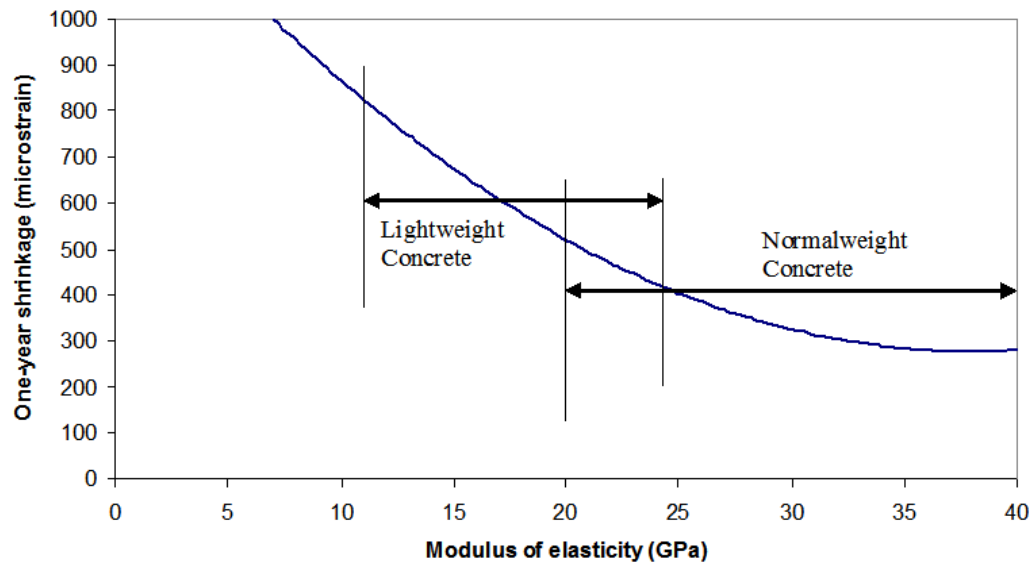


Figure 2.4 – Influence of modulus of elasticity of aggregates on drying shrinkage³¹

Further research has been performed to assess the difference in shrinkage between light-, normal- and heavyweight aggregates Portland cement concretes. The lightweight concretes that have lower shrinkage than conventional concrete are structural lightweight concretes, with high elastic modulus or between 24 and 29 GPa. Some of these researches will be looked at here.

Nilsen and Aïtcin³² considered the influence of aggregate density on mechanical properties of high-strength concrete. Five mixes were prepared and studied:

- NWC1 – using normalweight aggregate or natural granite glacial gravel & natural sand, $f_c=96.7\text{MPa}$ and $E_c=40\text{GPa}$ at 28 days
- HWC2 – using heavyweight aggregate or crushed ilmenite & natural sand, $f_c=82.3\text{MPa}$ and $E_c=52\text{GPa}$ at 28 days
- HWC3 – using heavyweight aggregate or crushed ilmenite & ilmenite sand, $f_c=78.9\text{MPa}$ and $E_c=60\text{GPa}$ at 28 days
- LWC4 – using lightweight aggregate or expanded shale aggregate, type L & natural sand, $f_c=90.5\text{MPa}$ and $E_c=29\text{GPa}$ at 28 days
- LWC5 – using lightweight aggregate or expanded shale aggregate, type H & natural sand, $f_c=73.8\text{MPa}$ and $E_c=26\text{GPa}$ at 28 days

The difference between aggregate L and H is in the structure, where L is one of the best lightweight aggregate due to its uniform microporosity and H is a typical ordinary lightweight aggregate. Standard ASTM procedures were used for mixing, casting and testing and all the coarse aggregates consisted of 5-10mm particles.

³¹ Mindess, S.; Young, J.F. & Darwin, D. 2003:428

³² Nilsen, U. & Aïtcin, P.C. 1992:8-12

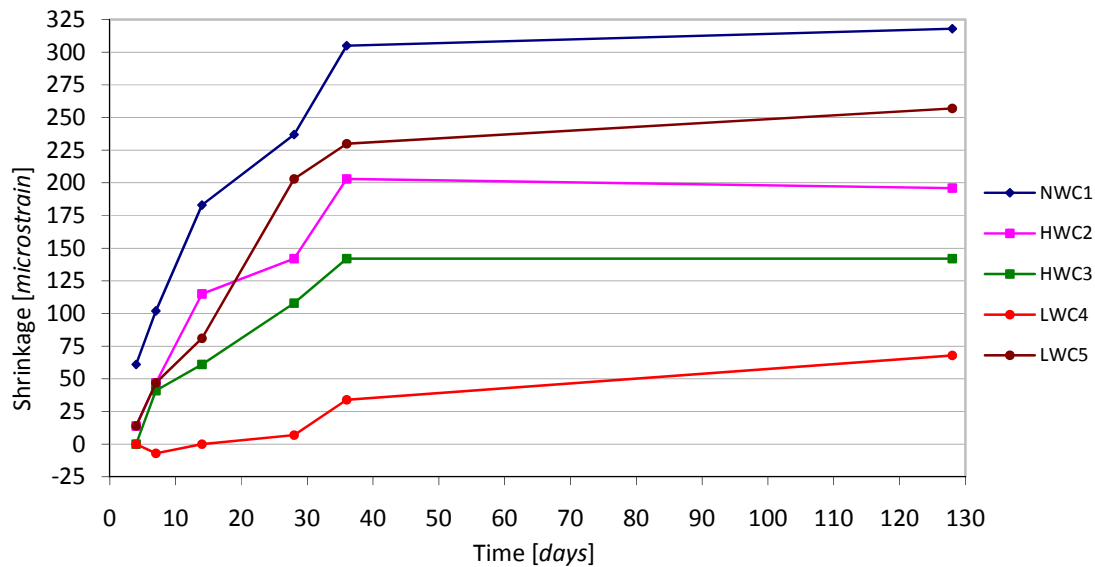


Figure 2.5 - Drying shrinkage after water curing the samples for 28days³³

From Figure 2.5 it should be noticed that the light- and heavyweight concrete is experiencing lower shrinkage than the normalweight concrete. The low shrinkage values for the LWC4 can be explained by the movement of water from the highly absorptive, saturated aggregate into the hydrating mortar. The difference in shrinkage between the two lightweight concrete mixes is at the same way due to different rate of water movement out of the aggregate particles. As a result to this experiment it was found that: “The lightweight concrete mixture containing a high-quality expanded shale aggregate showed that it is possible to make a very-high-strength lightweight concrete with almost negligible drying shrinkage.”³⁴

Zhang et al.³⁵ compared light- and normalweight aggregates concretes over a period of two years. The concretes had equivalent mixture proportions or similar 28day compressive strength. The modulus of elasticity was between 24-29GPa for the lightweight concrete and between 30-36GPa for the normalweight concrete. Expanded clay was used as lightweight aggregate and crushed granite and natural sand as normalweight aggregates.

³³ Nilsen, U. & Aitcin, P.C. 1992:11

³⁴ Nilsen, U & Aitcin, P.C. 1992:11

³⁵ Zhang, M.H.; Li, L. & Paramasivam, P., 2005:86-92

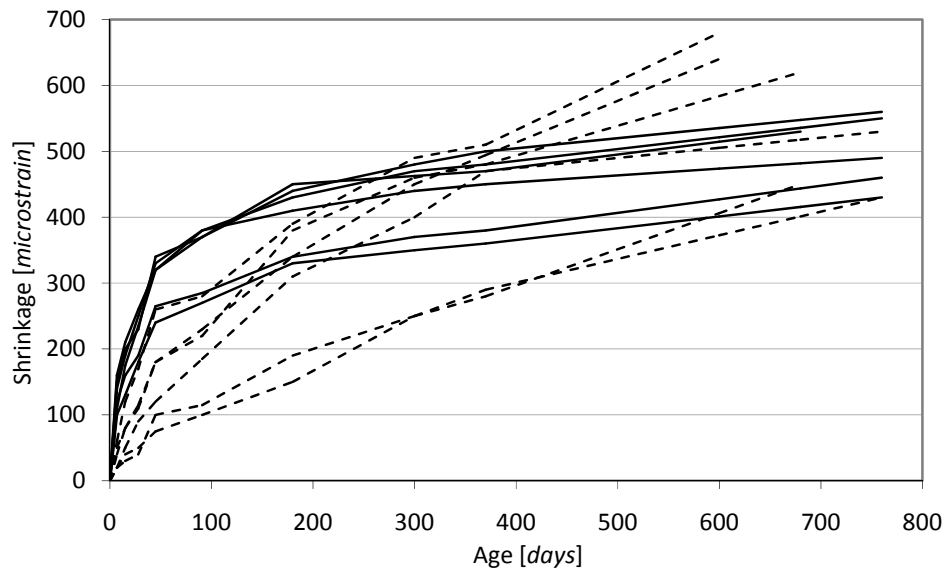


Figure 2.6 – Measured shrinkage of various light- (dashed lines) and normalweight (whole lines) concretes³⁶

Higher shrinkage is experienced in normalweight concrete in the first 6 months, whereas long term shrinkage was higher for the lightweight concrete, Figure 2.6. The internal curing of the lightweight aggregate had been attributed to reduce autogenous shrinkage of the lightweight aggregate which could explain low early age shrinkage. The drying shrinkage was expected to be the same in the normal- and lightweight concretes exposed to a dry environment, but the lightweight concrete has smaller autogenous shrinkage and therefore smaller total shrinkage within the first 6 months.

Newman³⁷ stated that lightweight concrete with dense fine aggregates exhibited similar shrinkage performance as normalweight concrete. It was also recorded that shrinkage cracking was rare in lightweight concrete due to the relief of restraint by creep and continuous supply of moisture from the pores of the lightweight aggregate.

Various types of lightweight aggregate concretes usually result in very different behaviour as far as drying shrinkage is concerned. Shrinkage is going to be one of the main concerns in the variable density concrete panel, since it contains light- and heavy/normalweight concrete which experience different shrinkage. Differential shrinkage within a member is the main factor causing warping of concrete.

2.2.4 Creep

Deformation of a material under short time loading is simultaneous with the increased load. When deformation continues with time while the load remains constant or deformation beyond that experienced as the material is initially loaded, is defined as creep.³⁸ The gradual increase in strain with time under load or the increase in strain under sustained stress in concrete is therefore due to creep. The increase in strain can be several times as large as the strain on loading, creep is

³⁶ Zhang, M.H.; Li, L. & Paramasivam, P., 2005:86-92

³⁷ Newmann, J.B. 1993

³⁸ Ugural, A.C. & Fenster, S.K. 2003:147

therefore of considerable importance in structures. Creep can also be in the form of relaxation, if a stressed concrete specimen is subjected to a constant strain, creep will manifest itself as a progressive decrease in stress with time.³⁹

Creep and drying shrinkage are commonly stated as interrelated phenomena as there are a number of similarities between the two:⁴⁰

- The strain-time curves are very similar
 - Experimental parameters affect in much the same way
 - Magnitudes of the strains are the same
 - They include considerable amount of irreversibility
- Like shrinkage, creep is a paste property that the aggregates try to restrain
 - The origins of creep and drying shrinkage are believed to reside in the response of calcium silicate hydrates to stress
 - The experimental variables affect creep and drying shrinkage

A considerable proportion of the total creep is irreversible. Typically, concrete dries while under load which results in greater creep deformations than if the concrete is dried prior to loading. Total creep strain (ϵ_{cr}) is the sum of ϵ_{bc} (basic creep – specimen loaded but not dried) and ϵ_{dc} (drying creep – excess deformation when specimen loaded and dried). In practice this distinction is ignored and creep is considered as the deformation under load in excess of free shrinkage. Creep is often described in terms of the creep coefficient:⁴¹

$$C = \frac{\epsilon_{cr}}{\epsilon_e}$$

Where, ϵ_{cr} and ϵ_e are the creep and instantaneous strains under the applied load.

Factors that influence creep are⁴²:

- **Applied stress** – up to about 50% of the ultimate strength of concrete, a linear relationship is between the creep strains and the applied stress is generally assumed. The concept of specific creep is based on this assumption, which allows creep to be compared for various concrete specimens loaded at different stress levels.

$$\text{specific creep } (\phi) = \frac{\epsilon_{cr}}{\sigma}$$

At higher stresses the deformation is not linear as micro cracking occurs. When estimating cracking potential due to stresses imposed by moisture or thermal changes the main focus is on creep in tension. Reduction of tensile stresses caused by tensile creep can minimize cracking in water-retaining structures and thin shell roofs. The initial rate of creep is higher in tension than in compression, tensile creep is therefore greater for relatively short durations of load, but at longer times the reverse may hold

- **Water/cement ratio** – the specific creep increases with increasing w/c ratio
- **Curing conditions** – as the degree of hydration is lower and the porosity of the paste is higher at shorter curing times, the time of moist curing at loading affects the magnitude of creep. The age effect on the other hand continues in more mature concretes where

³⁹ Neville, A.M. 1995:449

⁴⁰ Mindess, S.; Young, J.F. & Darwin, D. 2003:440-51

⁴¹ Mindess, S.; Young, J.F. & Darwin, D. 2003:440-51

⁴² Mindess, S.; Young, J.F. & Darwin, D. 2003:441-8

porosity and strength are not changing markedly with time, but is due to the aging effect for calcium silicate hydrates, which increases its resistance to stress. Increased temperature of curing, reduces basic and drying creep as higher temperatures increase the aging process of the calcium silicate hydrates

- **Temperature** – if concrete is maintained at higher temperatures while under load, the amount of creep increases. Creep increases approximately linearly with temperature up to 80°C, as a result of increased creep rate. Generally it is assumed that a maximum creep rate is gained between 50 and 90°C. Although creep develops faster at higher temperatures, the long term creep is lower due to aging. If the temperature increases as the concrete is being loaded, an additional creep strain component develops called transitional thermal creep
- **Moisture** – free moisture in concrete is necessary for creep to occur, the amount of creep is therefore reduced when situated at low relative humidity before external load is applied. When no evaporable water is present in concrete the amount of creep falls to zero.
- **Cement Composition** – increased C₃A content or decreased effective C₃S content seems to increase creep
- **Chemical admixtures** – admixtures that generally increase drying shrinkage also increase the amount of creep
- **Aggregates** – act as a restraint reducing potential deformations of the paste. The aggregate content and modulus of elasticity of the aggregates are therefore the most important parameters affecting creep of concrete. As the aggregate content and the elasticity increases, the creep reduces
- **Specimen Geometry** – when drying occurs while the concrete is under load, the specimen size and shape become important. As the volume to surface increases, the creep coefficient decreases

Gesoğlu et al⁴³ examined 12 lightweight aggregate concrete mixes for compressive strength, static elastic modulus, split-tensile strength, free shrinkage, weight loss, creep and restrained shrinkage. They found that:

- Crack opening on ring specimens was wider than 2mm for all concretes
- Free shrinkage, weight loss and maximum crack width increased with increased coarse aggregate content
- Specific creep, compressive and split tensile strengths and static elastic modulus decreased with increased coarse aggregate content
- Shrinkage cracking performance of lightweight concretes was significantly poorer than normal weight concrete

Higher shrinkage strains as well as more water loss was experienced for concretes incorporating lightweight aggregates in higher quantities. This was related to excess water in the mixture supplied by the saturated lightweight coarse aggregates. These are the same results as found by Nilsen and Aitcin⁴⁴ described earlier.

⁴³ Gesoğlu, M; Özturan, T. & Güneyisi, E. 2004

⁴⁴ Nilsen, U. & Aitcin, P.C. 1992:8-12

As the lightweight insulating layer is significantly weaker than the structural normal/heavyweight layer in the variable density concrete it was assumed that the concrete would warp due to differential shrinkage. Significant shrinkage was not observed which could be explained by creep in the lightweight concrete which is significantly weaker than the structural concrete. Creep is usually considered as an undesirable property of concrete but it can act as a mechanism of stress relief, reducing tensile stresses.

2.3 Serviceability

2.3.1 *Warping or curling of concrete*

Warping or curling is the out of plane deformation of a noncircular cross section that initially is in plane.⁴⁵ In other words, warping is the distortion of a slab or a beam into a curved shape by upward or downward bending of the edges.⁴⁶ Warping can be caused by various reasons but is usually due to size change, shrinkage or expansion within the member. Differential shrinkage is the primary characteristic that affects warping, where increased differential shrinkage leads to increased warping.⁴⁷ Despite the range of warping problems within concrete members, not much research has been carried out and most of them have been done on warping of concrete slabs. Dimensional incompatibility is a common problem in structural parts other than slabs and can be found to be one of the main reasons for failure in repaired concrete.⁴⁸ The remarks noticed for warping in concrete slabs should be transferrable directly to other concrete members experiencing warping.

When the top surface dries and shrinks with respect to the bottom surface, the member forms upward curling or becomes concave. This also happens during cold nights when the top layer cools down relative to the bottom layer. If on the other hand the bottom surface dries faster than the top surface the member becomes convex or forms downward curling. Downward curling also occurs when the top layer is exposed to the sun, as it will expand relative to the cool bottom layer.⁴⁹

⁴⁵ Ugural & Fenster, 2003:240

⁴⁶ NRMCA, 2006:1

⁴⁷ Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000:1

⁴⁸ McDonald, J.E.; Vaysburd, A.M. & Poston, R.W. 2000:1-12

⁴⁹ NRMCA. 2006:1

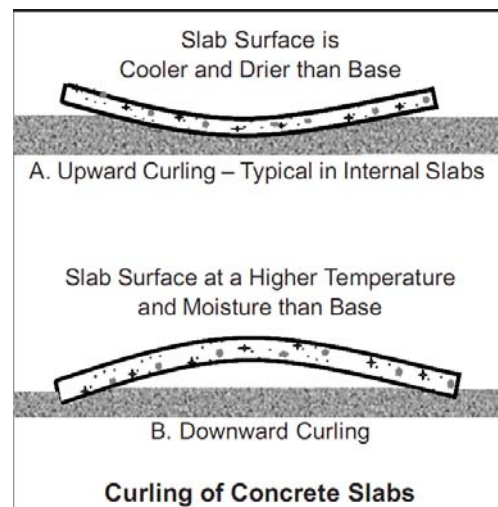


Figure 2.7 – Typical warping in concrete slabs⁵⁰

Curling is usually evident at early stage but slabs can though curl over an extended period. Curling soon after the placement is most likely related to poor curing and rapid surface drying due to excessive bleeding which can be caused by high water content, water sprayed on the surface or lack of surface moisture. That is slabs dry from top surface to the bottom, the moisture gradient through the slab creates differential shrinkage. Bleeding can be accelerated by placing concrete on a vapour retarder instead of an absorptive subgrade which causes increased shrinkage difference between top and bottom layers.⁵¹ Differential shrinkage can increase if the finishing techniques used induce the cement paste and fine aggregate to be concentrated at the surface. In cement rich mixes differential shrinkage rises as the heat produced as fresh concrete hardens increases.⁵²

The factors that determine the relative humidity and moisture gradient within the slab affect the amount of curling. The main factors controlling curling or dimensional changes in concrete are therefore:^{53 54}

- The concrete mix in terms of:
 - The water to cement ratio
 - The cement type
 - The aggregate type
- Construction practice or handling
- Service conditions
- Day-night temperature cycles
- The subbase, as coarse stiff soil provides better subbase than a fine graded more elastic soil

Preventing curling can be difficult but there are ways to help minimizing potential curling by controlling the amount of shrinkage.

⁵⁰ NRMCA. 2006:1

⁵¹ NRMCA. 2006:1

⁵² Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000:2

⁵³ NRMCA. 2006:1-2

⁵⁴ Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000:2-4

Severe warping occurred in some buildings in Perth, Western Australia. At first the warping was thought to be related to the use of white cement instead of Portland cement, but with further studies the warping behaviour was attributed to the lack of sand and excess cement in the mix design.⁵⁵ Shrinkage is usually reduced by using bigger aggregates; this indicates that shrinkage and therefore warping can be reduced by adding sand or other materials with intermediate density in the variable density panels. That is making the line where the density is changing wider. Covering the panels with an insulating mat is not likely to reduce the amount of curling since it did not affect the amount of curling in concrete slabs.⁵⁶

Different shrinkage within a member can be caused because of various reasons, but the most common ones are different temperature, moisture, stiffness (elastic modulus) or strength.⁵⁷ These situations can all be expected within the variable density concrete panel. Differential shrinkage is one of the main concerns when considering the variable density concrete panel since differential shrinkage can cause the panel to warp.

2.3.2 **Delamination**

Delamination develops inside the material without being obvious on the surface and is therefore an insidious kind of failure. Delaminations in concrete are mainly due to:⁵⁸

- Premature and improper finishing causing the slab surfaces (3 to 6mm) to separated from the base slab by a thin layer of air or water. Delamination occur when fresh concrete is sealed or densified by trowelling while the underlying concrete is still plastic, continuing to bleed and/or release air
- Corrosion of reinforcement steel near the concrete surface. The delaminations are formed when the reinforcing steel rusts and breaks the bond between the steel and surrounding concrete
- Poor bond between two-course placements, may cause delaminations or spalling

The delaminations caused by corrosion or poor bonding are generally thicker than those caused by improper finishing.

Delaminations usually do not become evident until after the concrete surface has set and dried, but are hard to detect during finishing. Delamination failure may be detected in the material by its sound, as solid composite has bright sound while the delaminated part sounds dull or hollowed when trapped with a hammer or heavy chain drag. More sophisticated methods are also available such as acoustic impact echo and ground penetrating radar.⁵⁹

Delamination is likely to occur in the variable density concrete if over vibrated. In these cases a paste layer develops between the structural and insulating layer. This can cause significant strength loss as the concrete breaks on the interfaces between the layers.

⁵⁵ Shayan, A. 1985:245

⁵⁶ Jeong, J.H. & Zollonger, D.G. 2004: 69

⁵⁷ Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000:1

⁵⁸ NRMCA. 2007:1

⁵⁹ NRMCA. 2007:1

2.4 Durability

Durability is the ability of a material or structure to withstand the service conditions for which it was designed, for a prolonged period without significant deterioration.⁶⁰ Despite the concrete having good mature after 28 days, the concrete will continue to mature and age depending on the original material composition and properties as well as the environmental actions during service.⁶¹ Changes and deterioration that occur in concrete follow from transport of various substances, but the three main transport mechanisms are:^{62 63}

- **Diffusion** which is the process by which liquid, gas or most commonly ions in concrete, move through a porous material under the action of concentration gradient. Diffusion is an important internal transport mechanism for most concrete structures exposed to salts and occurs in partially or fully saturated concrete. High surface salt concentrations are initially developed by absorption but then the salt migrates by diffusion to the internal material, where there are low concentrations of ions.
- **Absorption** is the process where fluid is drawn into a porous, unsaturated material under the action of capillary forces. The amount of capillary suction is dependent on:
 - The pore volume and geometry
 - The saturation level of concrete.

Water absorption caused by wetting and drying at the concrete surface, is an important transport mechanism near the surface but its significance decreases with depth. Sorptivity is defined as the rate of movement of wetting front through a porous material under the action of capillary forces.

- **Permeation** is caused by hydraulic gradient. That is permeation describes the process of movement of fluids through the pore structure of concrete under an externally applied pressure, as the pores are saturated with the particular fluid. Permeability therefore measures the capacity of concrete to transfer fluids by permeation. Permeability of concrete is dependent on:
 - The concrete microstructure
 - The moisture condition of the material
 - The characteristics of the permeating fluid

Movements of substances that cause deterioration are confined to the pore system, an inter-connected pathway through the material. The pores can either be:⁶⁴

- Compaction pores – are slightly inter-connected pores between 0.1-5mm in diameter
- Entrained air pores – are discrete bubbles around 0.1mm in diameter
- Capillary pores – are inter connected pores between 0.05-50microns in diameter
- Gel pores – are widespread and really small, generally less than 0.05microns in diameter

The concept of durability is hard to quantify since durability is not a property of a concrete material but a behaviour or performance of a concrete structure in certain exposure conditions.

⁶⁰ Mackechnie, J.R. 2006

⁶¹ Nilsson, L.O. 2003

⁶² Mackechnie, J.R. 2006

⁶³ Beushausen, H.D.; Alexander M.G. & Mackechnie, J.R. 2003

⁶⁴ Mackechnie, J.R. 2006

Service life, the time during which a concrete fulfils its performance requirements without non-intended maintenance, is a concept that is often used to describe the durability of concrete.⁶⁵ The basic nature of deterioration is mainly of three types:^{66 67}

- Chemical attack – dissolution of substances or chemical reactions between substances and components of the concrete. These attacks occur on concrete in aggressive water containing acids, sulphates or sewage
- Physical attack – can be a non-reacting liquid, or heat, penetrating into concrete or a concrete component, causing internal stresses and expansion. Physical processes includes cracking, abrasion, erosion and frost attacks, or attacks on the concrete surface
- Electrochemical attack – chemical reactions at the anode and cathode are combined with an electrical current through the steel and through the concrete. Reinforcement corrosion is therefore electrochemical attack

Often, several chemical and physical reactions are combined with one or several transport processes, which usually determine the rate of deterioration. The permeation properties of hardened concrete determine the transport processes occurring in the pore system of concrete. The permeation often determines the durability and service life of concrete.⁶⁸

2.4.1 ***Corrosion of reinforcing steel***

Corrosion of reinforcement is prevented by the strong alkaline nature of $\text{Ca}(\text{OH})_2$ (pH of about 13). This protection is known as passivation and is formed by a thin protective film of iron oxide on the metal surface. In permeable concrete, corrosion of reinforcement will take place if the alkalinity is reduced by.⁶⁹

- Carbonation reaching the concrete in contact with the steel, lowering the pH to about 9
- Soluble chlorides penetrating all the way to the steel and the pH value falls below 11.0

Corrosion causes cracking and spalling of cover concrete as a result of expansion of corrosion product, that is rust and pitting caused by reduction of cross sectional area of reinforcement bars. Chloride-induced and carbonation-induced corrosions need to be treated differently as the chloride-induced corrosion causes far worse damage.⁷⁰ For corrosion to take place, both water and oxygen must be present. In a completely dry atmosphere or where the relative humidity is below 40%, no corrosion will take place. Neither will corrosion take place in concrete that is fully immersed in water. The optimum relative humidity for corrosion is approximated between 70 and 80%.⁷¹

Chloride-induced corrosion initiates when chloride levels in concrete reach a certain threshold, either during mixing or by ingress from the environment. The time for the chlorides to penetrate

⁶⁵ Nilsson, L.O. 2003

⁶⁶ Nilsson, L.O. 2003

⁶⁷ Mackechnie, J.R. 2006

⁶⁸ Nilsson, L.O. 2003

⁶⁹ Neville, A.M. & Brooks, J.J. 1987:275-282

⁷⁰ Mackechnie, J.R. 2006a

⁷¹ Neville, A.M. & Brooks, J.J. 1987:275-282

into the concrete, and reach a critical chloride concentration at the steel surface is dependent on the following:⁷²

- Depth of concrete cover
- Chloride resistant of concrete
- Use of cement extender, such as fly ash, slag or microsilica
- Type of reinforcement, that is plain, galvanized or stainless steel

In carbonation-induced corrosion, the principal mechanism is carbonation from carbon dioxide but sulphur dioxide can also cause the acidification. As the carbonation front moves with the square root of time, carbonation is relatively slow process in concrete, leaving most structural concretes with long-term carbonation rates below 1.0mm a year. The rate of carbonation is affected by:⁷³

- The moisture content of the concrete
- The gas permeability of the concrete
- The calcium hydroxide content of the material

The extent, severity and implications of corrosion damage depend among other things on:⁷⁴

- Geometry of the element, as big bars at low covers generate large spalling pressures
- Cover depth of reinforcement, as deep cover may prevent full oxidation and expansion of rust
- Moisture condition, as conductive electrolytes encourage well defined macro-cells and allow more rapid corrosion
- Age of structure, as rust stains progress to cracking and then to spalling
- Rebar spacing, as closely spaced bars in walls and slabs encourage delamination along the line of least resistance
- Crack distribution, as cracks provide low resistance path to the steel for oxygen and water
- Service stresses, as corrosion may be accelerated in highly stressed zones

2.4.2 **Alkali silica reaction**

Alkali silica reaction (ASR) is the process when concrete expands and gets damaged by a chemical reaction between the active silica constituents of the aggregate and the alkalis in the cement.⁷⁵ For ASR damage to occur, three things must happen simultaneously:⁷⁶

- The concrete must contain reactive aggregate
- The alkali content of the cement must be high
- The concrete must be almost too fully saturated

Opal, chalcedony and tridymite are the reactive forms of silica and the reaction starts as an attack of the siliceous minerals by the alkaline hydroxides derived from the alkalis. This reaction forms an alkali-silicate gel that attracts water by absorption or osmosis which increases its volume

⁷² Mackechnie, J.R. 2006a

⁷³ Mackechnie, J.R. 2006a

⁷⁴ Mackechnie, J.R. 2006a

⁷⁵ Neville, A.M. & Brooks, J.J. 1987:273

⁷⁶ Mackechnie, J.R. 2006a

causing the surrounding cement paste to expand, crack and disrupt. This leads to pop outs, spalling, restrained cracking along the line of reinforcing bars or map cracking of the concrete. There are two reasons for the expansion of the cement paste; that is the hydraulic pressure generated by osmosis or the swelling pressure of the still solid products of the alkali-silica reaction. The size of the siliceous particles controls the occurrence speed of the reaction, having fine particles leading to expansion within weeks while larger ones do so after some years. It is known that certain types of aggregates tend to be reactive but it is hard to determine whether a given aggregate will cause excessive expansion because of reaction with the alkalis in cement.⁷⁷

It is hard to prevent ASR but some precautions are recommended to minimise the risk:⁷⁸

- Prevent external source of moisture contacting the concrete
- Use Portland cements with low alkali content
- Substitute some of the ordinary Portland cement with ground granulated blast-furnace slag or fly ash
- Limit the alkali content of the concrete
- Use a combination of aggregates that are considered potentially safe

2.5 Thermal properties of concrete

Heating residential houses and other buildings is essential in cold countries. In hot countries the buildings need to be able to retain the heat of the day and release it again at night time. Buildings in these countries should therefore have suitable thermal insulating properties to save heating energy and thermal capacity to stabilize the internal temperature.⁷⁹

Heavy structures stabilize the temperature better than light ones, but the outside temperature changes the inside temperature if a structure has bad thermal insulation (the external structures) and capacity to restore and stabilize conditions (the frame). The effective factors in thermal capacity are the weight of the structure and the specific heat capacity of the material.⁸⁰ Looking at a wall, the rate of the heat loss is dependent upon: the temperature difference between the inner and outer surface, the porosity and the thermal transmittance (U-value).⁸¹

The Cement and Concrete Association of New Zealand examined the benefits of building concrete houses in New Zealand. The work confirmed that high mass constructions are well suited to New Zealand conditions. The main findings in this research were:⁸²

- Amount and orientation to the sun of glazing, has a significant effect on thermal performance of a home
- Concrete houses used 15.5% less energy than identical timber ones for similar comfort conditions
- Concrete houses were more comfortable when a large window was fitted, since the timber house overheated significantly

⁷⁷ Neville, A.M. & Brooks, J.J. 1987:273-5

⁷⁸ Neville, A.M. & Brooks, J.J. 1987:273-5

⁷⁹ Bobrowski J. 1978:5

⁸⁰ Bobrowski J. 1978: 14-15

⁸¹ Park, Yoo Shin. 2005: 1-2

⁸² CCANZ. 2007

- The concrete house was more than 5°C cooler than ambient on a 30°C day, while inside the timber one, it was approximately same temperature as outside
- Overnight, the concrete house was on average, 1°C warmer than the timber house
- Minimum temperatures for the concrete and timber houses were 15.6°C and 12.8°C.
- The timber house required four times the shading needed by the concrete house to control overheating.

The New Zealand Standard (NZS 4218)⁸³ allows three alternative methods of determining the insulation requirements of homes:

- Prescribed R values for various building elements
- Allows some R values to be reduced, provided these are compensated for by higher R values elsewhere in the building
- Sophisticated computer modelling techniques to model thermal performance more accurately

2.5.1 *Thermal conductivity*

Thermal conductivity measures the ability of a material to conduct heat and is defined as the ratio of heat flux to temperature gradient. The thermal conductivity of ordinary concrete depends on its composition e.g. aggregate type and the degree of saturation. Moist concrete has higher thermal conductivity while long term drying reduces it. When the concrete is saturated its thermal conductivity usually varies between 1.4-3.6 J/m²s°C/m (1.4-3.6 W/mK). Mineralogical character of the aggregate greatly affects the conductivity of the ordinary concrete and in general, crystallinity of rock increases its conductivity. Generally, basalt and trachyte have a low conductivity, dolomite and limestone are in the middle range, and quartz exhibits the highest conductivity, which depends also on the direction of heat flow relative to the orientation of the crystals.⁸⁴

Density does not considerably affect the conductivity of ordinary concrete but thermal conductivity of lightweight concrete varies with its density, due to the low conductivity of air as can be seen on Figure 2.8.⁸⁵ The greater the density of lightweight aggregate concrete the higher the thermal conductivity and strength but lower thermal insulation is provided by the concrete. The binder type used also affects the thermal performance, since inorganic polymer gives lower thermal conductivity than similar Portland cement binder.⁸⁶ Lightweight concrete has much lower thermal conductivity than ordinary concrete, but it is difficult to get the thermal conductivity value below 0.2 W/mK.

⁸³ NZS 4218. 2004

⁸⁴ Neville, A.M. 1995:374-5

⁸⁵ Neville, A.M. 1995:375

⁸⁶ Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

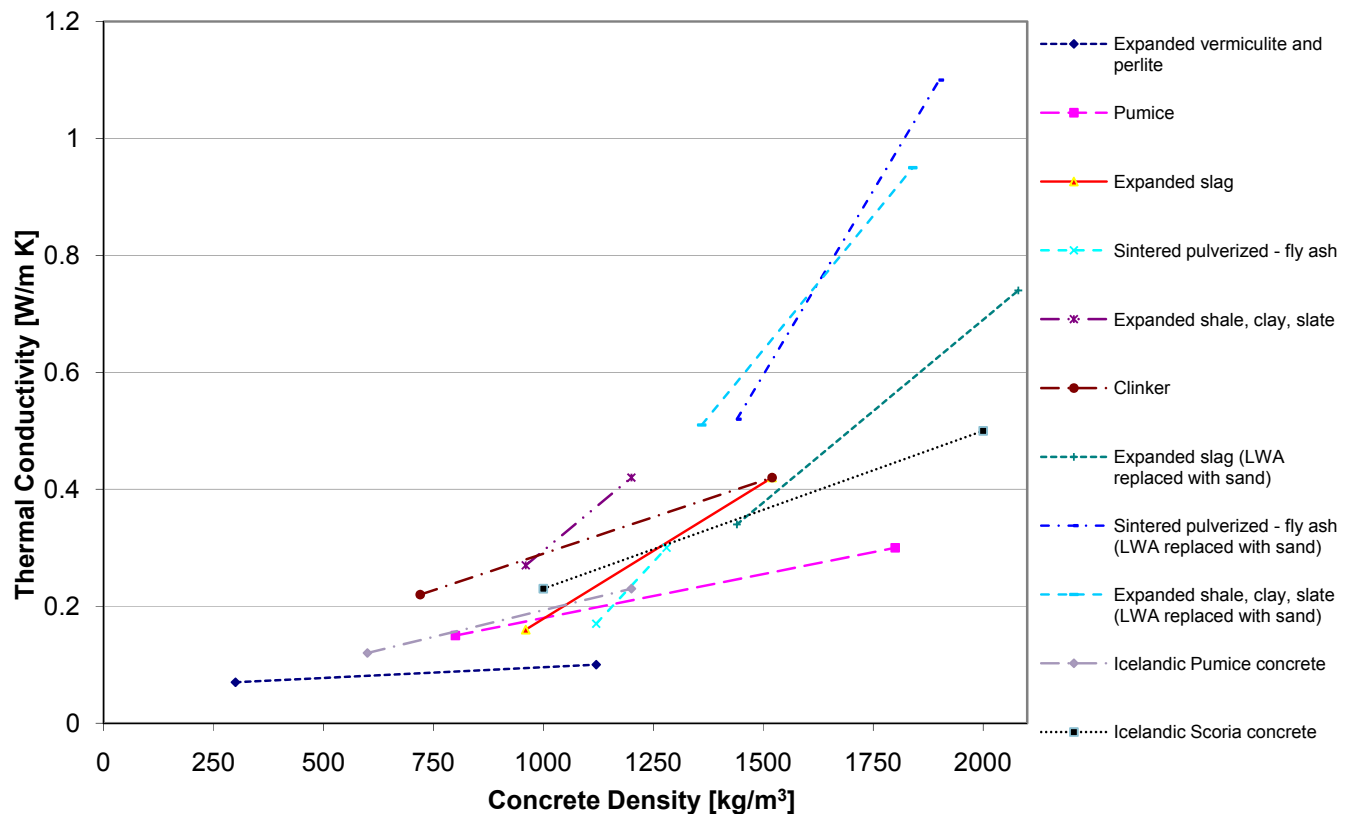


Figure 2.8 – Concrete density versus thermal conductivity of different lightweight aggregate concretes^{87 88}

2.5.2 Specific heat

Specific heat of a material is the amount of heat per unit mass required to change the temperature by one degree. The specific heat therefore represents the heat capacity of concrete. The higher the specific heat, the more heat energy is required to increase the temperature of the concrete, where the relationship between specific heat capacity and heat energy is:⁸⁹

$$Q = m \times c \times \Delta T$$

Where Q is the heat energy put into or taken out of the substance, m is the mass, c is the specific heat capacity and ΔT is the temperature differential.

Specific heat is a little affected by the mineralogical character of the aggregate, but is considerably increased by an increase in the moisture content of the concrete. The specific heat increases with an increase in temperature and with a decrease in the density of concrete. Specific heat of ordinary concrete is between 0.5-1.17 kJ/kgK and is determined by elementary methods of physics. The specific heat of water is 4.2 kJ/kgK and timber has 2.1 kJ/kgK, concrete has therefore

⁸⁷ Mindess, S.; Young, J. F. & Darwin, D. 2003: 548

⁸⁸ Ásgeirsson, H. 1994:19

⁸⁹ BBC – Education Scotland. 2007

relatively low specific heat. The specific heat is important when considering thermal mass of structure (i.e. with respect to thermal storage).^{90 91}

2.5.3 *Thermal mass*

Traditional concrete is considered a poor insulator but with good thermal mass, or fabric energy storage. Thermal mass is the ability of material to absorb and store thermal energy with its mass. That is, concrete absorbs thermal energy when the internal temperature is higher than the concrete temperature, stores it, and releases it again when the internal temperature drops below that of concrete. Due to thermal mass, solid construction buildings usually feel cooler during summer and warmer during winter. That is, temperature fluctuations are reduced and a more comfortable home is the result.⁹² Products such as insulating concrete forms have greatly improved insulation but these products prevent the full thermal mass of concrete being utilized.

Materials with high specific heat, high density and relatively low thermal conductivity are ideal for good thermal mass. These materials are for example: adobe, earth, stone, concrete and water. In other words, materials that are good for thermal mass are able to slowly store, and slowly release, relatively large quantities of heat per unit mass compared to other materials. Timber has a high specific heat but low density and has therefore poorer thermal storage than concrete. The volumetric heat capacity of concrete is about $2.0 \times 10^6 \text{ J/m}^3 \text{ K}$, while timber only has about $1.1 \times 10^6 \text{ J/m}^3 \text{ K}$.⁹³

Insulating materials normally have much lower thermal conductivity than materials used for thermal storage or as a thermal mass. A material with high thermal conductivity releases its stored heat too quickly to work well as thermal mass. Conversely, a material with extremely low thermal conductivity (like insulating materials) will take too long to absorb and store heat. Therefore materials with low but not excessively low thermal conductivity are needed to provide a good thermal mass.

Walls used for thermal mass need to have the appropriate thickness, to stabilize the internal temperature. Too thin wall will penetrate heat into the living space during the day, when it is not needed, and have insufficient stored heat to keep the living space warm during the night. If the wall is too thick, the heat will take too long to penetrate the wall, when it finally reaches the living space there may be no need for extra heat.

2.5.4 *Total thermal resistance (R-value)*

The thermal performance of buildings is often assessed by using the R-value which is a measure of thermal resistance. The R-value is a measure of products insulating ability, calculated from the thermal conductivity and the thickness of the material ($\text{R-value} = \text{thickness/thermal conductivity}$) and is expressed in $\text{m}^2 \text{ K/W}$. A building product with high R-value has more resistance to heat loss in winter and heat gain in summer than a product with low R-value.

⁹⁰ Mackechnie, J.R. 2006

⁹¹ Neville, A.M. 1995:377

⁹² Cement and Concrete Association of Australia. 2005:1

⁹³ Bellamy, L. 2007

Table 2.1 - R-values for some typical concrete wall systems⁹⁴

System	R value °C/W
Strapped (25mm) & lined 150mm concrete masonry (with reflective foil)	0.85
Strapped (25mm) & lined 150mm concrete masonry (pumice aggregate)	0.63
Strapped & lined 150mm concrete masonry (with 25mm polystyrene insulation)	1.00
200mm cavity insulated concrete masonry block (Partially filled)	0.73
250mm cavity insulated concrete masonry block (Partially filled)	1.00
150mm concrete masonry block with 50mm expanded polystyrene exterior insulation	1.70
Precast panel with polystyrene (50mm polystyrene) cast in	1.61
200mm insulated concrete formwork block	2.98

For a 200mm thick wall with thermal conductivity of $0.2W/mK$ the R-value would be $1m^2K/W$. New Zealand is divided into three climate zones with different R-values requirements.^{95 96}

- Zone 1 – Auckland and Northland with minimum R-value of $0.6m^2K/W$
- Zone 2 – Remainder of the North Island with minimum R-value of $0.6m^2K/W$
- Zone 3 – South Island and Central North Island with minimum R-value of $1m^2K/W$

These requirements are increasing in 2007 and 2008 to:⁹⁷

- Zone 1 – minimum R-value of $0.8m^2K/W$ in September 2008
- Zone 2 – minimum R-value of $1.0m^2K/W$ in June 2008
- Zone 3 – minimum R-value of $1.2m^2K/W$ in October 2007

Most standards recognise the benefit of thermal mass effect of concrete, less insulation is therefore required for concrete homes. A lower R-value is required for solid constructions providing good thermal mass.⁹⁸

2.6 Materials

2.6.1 *Lightweight concrete*

Lightweight concrete is either produced from lightweight aggregate or by aeration which reduces the self weight of the concrete. It can be produced by introducing new materials which can be divided into three groups:⁹⁹

- Gassing agents such as aluminum powder or foaming agents
- Lightweight mineral aggregate such as perlite, vermiculite, pumice, expanded shale, slate, clay, etc.
- Plastic granules as aggregate e.g. polystyrene or other polymer materials

⁹⁴ CCANZ, 2007

⁹⁵ CCANZ, 2007

⁹⁶ NZS 4218, 2004

⁹⁷ CCANZ, 2007a

⁹⁸ CCANZ, 2007

⁹⁹ Sussman V. 1975

Lightweight concrete is often classified by the relationship between its cement content, compressive strength and unit weight to insulating, moderate strength and structural concrete, as listed in Table 2.2 and showed on Figure 2.9.

Table 2.2 - Classification of lightweight aggregate concrete^{100 101}

Lightweight aggregate concrete	Dry Density [kg/m ³]	Strength Range [MPa]	Main use
Low density concrete (Insulating concrete) No fines concrete, porous, cement-paste does not fill all the volume between aggregate particles	300 – 800	0.7 – 2	Cast in situ insulation Insulating layer in the prefabricated elements
Moderate-strength concrete (Structural insulating concrete) Low porosity between aggregate particles	600 – 1300	7 – 14	Load-bearing and insulating constructions Lightweight blocks and bricks
Structural concrete Dense concrete	1300 – 2000	17 – 63	Structures where strength is required and thermal insulation is not as big issue, reducing the total cost.

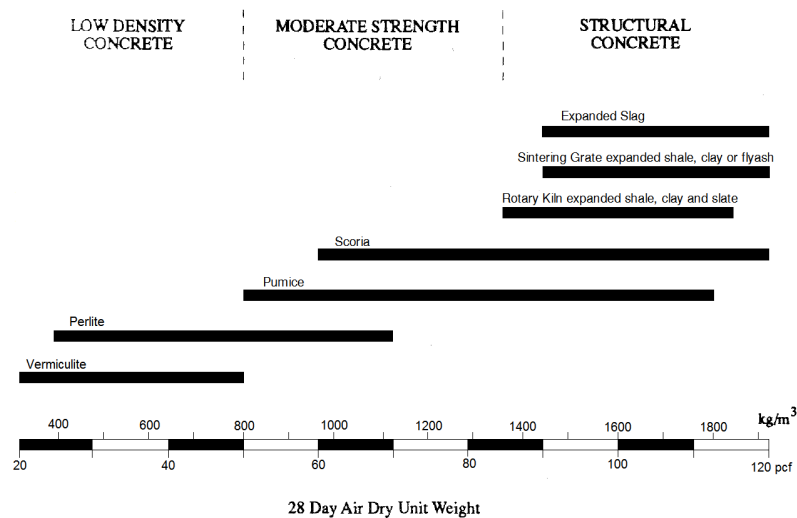


Figure 2.9 – Classification and unit weight of lightweight aggregate concrete¹⁰²

The structural lightweight concrete is usually made with coarse and fine aggregates but it is common to replace all or part of the fine fraction with normalweight sand.¹⁰³ To obtain high strengths in lightweight concretes, a low w/c ratio is necessary, generally resulting in higher cement and mineral admixture contents than in normal weight concrete of the same strength. The higher the density of the concrete the higher compressive strength is gained, but different strength of lightweight concrete is mainly gained by using different aggregates, as can be seen on Figure 2.10. When comparing self-compacting lightweight concrete containing glass

¹⁰⁰ Bobrowski J. 1978:16

¹⁰¹ Mindess, S.; Young, J. F. & Darwin, D. 2003: 548

¹⁰² Ásgeirsson, H. 1994:11

¹⁰³ Mindess, S.; Young, J. F. & Darwin, D. 2003: 549

powder¹⁰⁴, EPS (expanded polystyrene) concretes¹⁰⁵ and lightweight aggregate concrete made from dredged silt¹⁰⁶; the compression strength always increases with increased density.

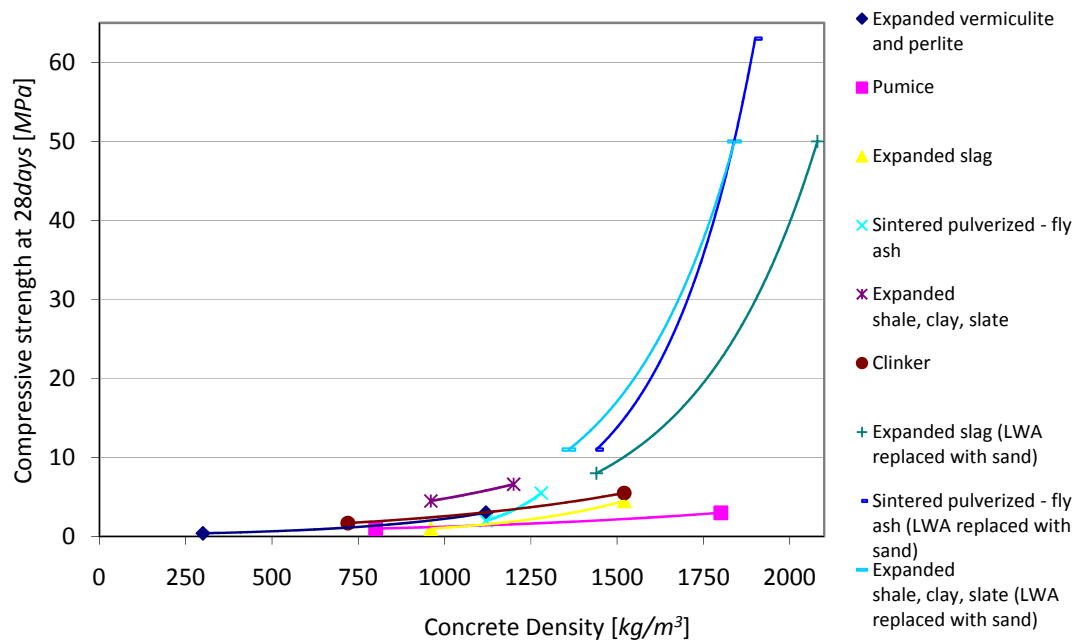


Figure 2.10 – Density versus strength of lightweight concrete using different lightweight aggregates¹⁰⁷

As the density and compression of strength of the lightweight concrete increases the thermal conductivity increases as well. It is therefore hard to combine good strength and good thermal insulation, as can be seen on Figure 2.11.

¹⁰⁴ Shi, C.; Wu, Y., 2005:355-363

¹⁰⁵ Babu, D.S., Babu, K.G., Tiong-Huan, W, 2006: 520-527

¹⁰⁶ Wang HY, Tsai KC, 2006:481-485

¹⁰⁷ Mindess, S.; Young, J. F. & Darwin, D. 2003: 548

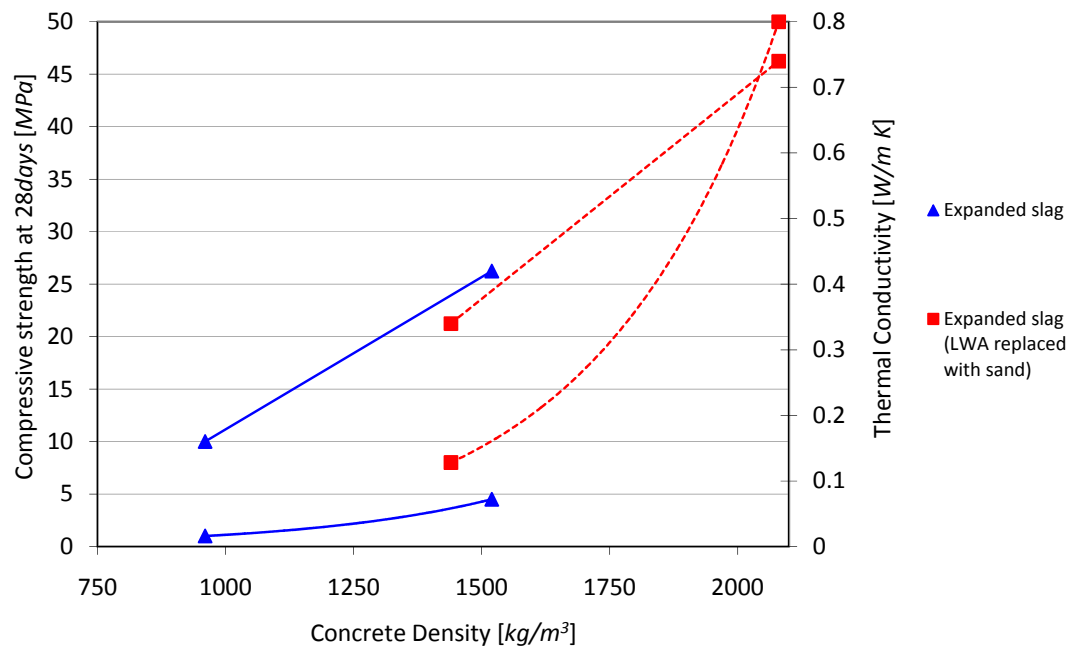


Figure 2.11 – Density, compressive strength and thermal conductivity of lightweight concrete¹⁰⁸

The paste weight is approximately one fourth of the total weight in conventional concrete but around one third or a half of the plastic lightweight concrete. The density of lightweight aggregate simulates more to the paste density than the normalweight aggregate; the lightweight concrete should therefore have less segregation tendency than conventional concrete as well as the aggregates tend to flow up instead of sinking.¹⁰⁹

Despite abundant research on the development and manufacturing techniques of lightweight concrete, its use in construction is less common than conventional concrete. Its properties such as strength, durability, heat and sound insulation and fire resistance have been proved to be good. The reduced self-weight of lightweight concrete provides smaller gravity loads and seismic internal masses which provides smaller member sizes and foundation forces.

More research needs to be done on different materials used in lightweight concrete. There is great potential to use recycled materials as aggregates and it is becoming more popular as the knowledge about its behaviour increases. Precast panels made of lightweight concrete are usually reinforced with fibres rather than conventional steel reinforcing and can have a variety of finishes applied or cast integrally on the surface.¹¹⁰

2.6.2 Inorganic polymer concrete

Production of inorganic polymer concrete is similar to ordinary Portland cement concrete. The same aggregates are used and mix designs are similar but ordinary Portland cement and water is replaced by inorganic polymer cement (IPC) binder and activating solution.¹¹¹

¹⁰⁸ Mindess, S.; Young, J. F. & Darwin, D. 2003: 548

¹⁰⁹ Ásgeirsson, H. 1994:13

¹¹⁰ CCANZ. 2007

¹¹¹ Keyte, L. and Lloyd, R. 2007

Inorganic polymer concretes are made by using IPC as a binder, consisting primarily of pozzolanic materials.¹¹² Inorganic polymer concretes (IPCs) are predominantly made from industrial waste materials; such as fly ash, granulated blast furnace slag, mine tailings (certain naturally occurring minerals) and contaminated soil (thermally activated clays). These materials are often referred to as geopolymers or alkali activated cements, as they all contain aluminium and silicon species which are soluble in highly alkaline solutions. Pozzolanic cements such as Portland cement contain high amount of calcium, forming calcium silica hydrates (CSH) for matrix formation and strength.¹¹³ The inorganic polymer cements contain substantially less calcium making them less reactive than pozzolanic cements. To activate the inorganic polymer cement, an alkali or alkali-silicate activating solution is used to dissolve the silica and alumina from the binder material. Silicate and aluminate species undergo condensation reactions when in a solution. Continuing dissolution and reaction of the silicate and aluminate species result in the formation of an alkali aluminosilicate gel, primarily amorphous, despite it possibly containing crystalline zeolites. As mentioned before, the CSH forms matrix formation and strength for pozzolanic cements but the alkali aluminosilicate gel provides matrix formation and strength of inorganic polymer cement.¹¹⁴ This simplified geopolymerization reaction mechanism is shown on Figure 2.12, despite being presented linearly, these processes are largely coupled and occur concurrently.

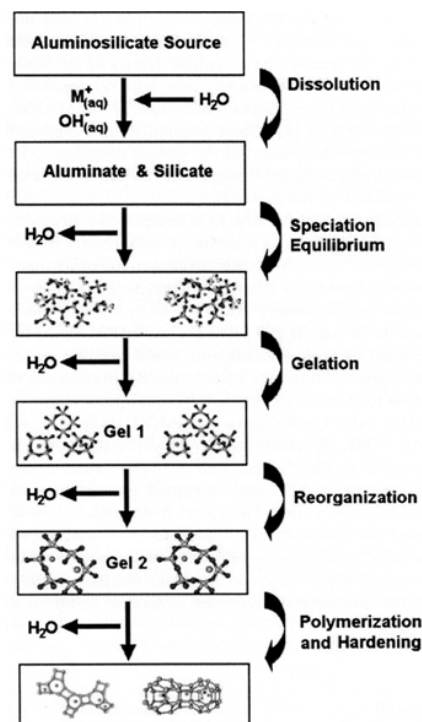


Figure 2.12 – Conceptual model for geopolymerization¹¹⁵

¹¹² Keyte, L. and Lloyd, R. 2007

¹¹³ Yip, C.K. 2004

¹¹⁴ Keyte, L. & Lloyd, R. 2007

¹¹⁵ Duxson, P.; Fernández-Jiménez, A; Provis, J.L.; Lukey, G.C.; Palomo A. & Van Deventer, J.S.J. 2007:2919

The structural difference between inorganic polymer cement and pozzolanic cements, give inorganic polymer concrete certain advantages, such as an earlier gain in strength.¹¹⁶ The raw materials and processing conditions, determine the setting behaviour, workability as well as the chemical and physical properties of the inorganic polymer concrete. The concrete can exhibit a wide variety of properties and characteristics, such as high compressive strength, low shrinkage, fast or slow setting, acid resistance, fire resistance and low thermal conductivity.¹¹⁷ It has been established that in many cases inorganic polymer concretes outperform their ordinary Portland cement counterparts with respect to compressive strength¹¹⁸ as well as acid and fire resistance.¹¹⁹ ¹²⁰ Similar to ordinary Portland cement based concretes, most mechanical properties of the inorganic polymer concrete depend upon the mix design and the curing method.¹²¹ The rheology of inorganic polymer concrete can be significantly different than of ordinary Portland cement concrete, as the viscosity is generally higher and yield shear stress usually lower.¹²² The inorganic polymer concrete formulations have also been shown to be cost-competitive with ordinary Portland cement concrete.^{123 124}

¹¹⁶ Van Jaarsveld, J.G.S. 2000

¹¹⁷ Duxson, P.; Fernández-Jiménez, A; Provis, J.L.; Lukey, G.C.; Palomo A. & Van Deventer, J.S.J. 2007

¹¹⁸ Van Jaarsveld, J.G.S. 2000

¹¹⁹ Davidovits, J. & Davidovics, M. 1988

¹²⁰ Lukey, G.C. & Van Deventer, J.S.J. 2003

¹²¹ Sofi, M.; Van Deventer J.S.J.; Mendis, P.A. & Lukey, G.C. 2007

¹²² Keyte, L. & Lloyd, R. 2007

¹²³ Lukey, G.C. & Van Deventer, J.S.J. 2003

¹²⁴ Van Deventer, J.S.J. 2002

2.7 References

- American Concrete Institute, ACI. 2000. ACI 116R-00: Cement and Concrete Terminology. American Concrete Institute, USA.
- Ásgeirsson, Haraldur. 1994. *Hekla Pumice in Lightweight Concrete*. Rannsóknarstofnun byggingariðnaðarins (The Icelandic Building Research Institute), Reykjavík, Iceland.
- Babu, Daneti Saradhi; Babu, K. Ganesh; Tiong-Huan, Wee. 2006. "Effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete." *Cement & Concrete Composites* 28:520-527.
- Banfill, PFG, "The rheology of fresh cement and concrete – a review", Proc. of 11th ICCC Conference, Durban, 2003, CSSA.
- BBC – Education Scotland. 2007, 7th of October. "*Specific heat capacity and calculating heat energy*." Web site: <http://www.bbc.co.uk/scotland/education/>
- Bellamy, Larry. 2007. Lecture notes in ENCI 621, *Concrete Materials and Practice*, 4th April. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Beushausen. H.D.; Alexander M.G. & Mackechnie, J.R. 2003. "Concrete durability specifications in an international context" *Betonwerk + Fertigteil-Technik, Concrete Plant + Precast Technology* 7:22-32.
- Bobrowski, Jan. 1978. *FIP State of Art Report: Principles of thermal insulation with respect to lightweight concrete*. Cement and Concrete Association, Wexham Springs, England.
- Bui, V.K.; Montgomery, D.; Hinczak, I. & Turner, K. 2002. "Rapid testing method for segregation resistance of self-compacting concrete." *Cement and Concrete Research* 32:1489-1496.
- CCANZ, Cement & Concrete Association of New Zealand. 2006. *Concrete Testing, CCANZ One Day Courses*. CCANZ, Cement & Concrete Association of New Zealand, Wellington, New Zealand.
- CCANZ, Cement & Concrete Association of New Zealand. 2007, 23th of August. *Thermal Performance of High Mass [Concrete] Houses*. Web site: <http://www.cca.org.nz>.
- CCANZ, Cement & Concrete Association of New Zealand. 2007a, December. *Information Bulletin: IB 87. Concrete Masonry, Compliance with Clause H1 – Energy efficiency*. CCANZ, Cement & Concrete Association of New Zealand, Wellington, New Zealand.
- Cement and Concrete Association of Australia. 2005. *Thermal benefits of 'solid' construction*. Australia.
- Chia, Kok-Seng; Kho Chen-Chung & Zhang, M.H. 2005. Stability of Fresh Lightweight Aggregate Concrete under Vibration. *ACI Materials Journal* 102:347-354.
- Davidovits, J. & Davidovics, M. 1988. Geopolymer: room temperature ceramic matrix for composites. *Ceramic Engineering and Science Proceedings* 9:835-842.
- Duxson, P.; Fernández-Jiménez, A; Provis, J.L.; Lukey, G.C.; Palomo A. & Van Deventer, J.S.J. 2007. *Geopolymer technology: the current state of art*. *Advances in Geopolymer Science & Technology* 42: 2917-2933.

- Gesoğlu, M; Özturan, T. & Güneyisi, E. 2004. Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. *Cement and Concrete Research* 34:1121-1130.
- Jeong, Jin-Hoon and Zollinger, Dan G. 2004. *Early-Age Curling and Warping Behaviour; Insights from a Fully Instrumented Test-Slab System*. Transportation Research 1096: 66-74.
- Keyte, Louise and Lloyd, Redmond. 2007. “*Stratified Panel IPC report*” September 2007, University of Canterbury, Christchurch, New Zealand.
- Lukey, G.C. & Van Deventer, J.S.J. 2003. Drivers for Establishment of a Geopolymer Industry, Materials 2003, Adaptive Materials for a Modern Society, Institute of Materials Engineering Australia.
- Mackechnie, J.R. 2006. Lecture notes in ENCI 621, *Concrete Materials and Practice*, second semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R. 2006a. Lecture notes in ENCI 426, *Concrete Structures*, first semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007. “Stratified Precast Concrete Panels for Buildings.” *Concrete Plant International*, July 2007.
- Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000. *Curling of Concrete Slabs on Grade*. Construction Technology Update No. 44. National Research Council Canada. Web site: http://irc.nrc-cnrc.gc.ca/pubs/ctus/44_e.html.
- McDonald, James E.; Vaysburd, Alexander M. & Poston, Randall W. 2000. *Performance Criteria for Dimensionally Compatible Repair Materials*. High-Performance Materials and Systems Research Program, Information Bulletin.
- Mindess, Sidney; Young, J. Francis; Darwin, David. 2003. *Concrete*. Second Edition. Pearson Education, Upper Saddle River, New Jersey.
- National Ready Mix Concrete Association (NRMCA). 2006, 18th August. *Concrete in Practice – Curling of concrete slabs*. Web site: <http://www.nrmca.org>.
- National Ready Mix Concrete Association (NRMCA). 2007, 22nd October. *Concrete in Practice (CIP20) – Delamination of Troweled Concrete Surfaces*. Web site: <http://www.nrmca.org>.
- Neville, A.M. 1995. “*Properties of Concrete*” Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- Neville, A.M. & Brooks, J.J. 1987. “*Concrete Technology*” Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- Newman, J.B. 1993. Properties of structural lightweight aggregate concrete in J.L. Clarke (Ed.), *Structural Lightweight Aggregate Concrete*, Chapman & Hall, London, England.
- Nilsen, Ulrik; Aïtcin, Pierre-Claude. 1992. “*Properties of High-Strength Concrete Containing Light-, Normal-, and Heavyweight Aggregate*.” *ASTM Journal of Cement, Concrete, and Aggregates* 14:8-12.
- Nilsson, Lars-Olof. 2003. Durability concept; pore structure and transport processes in John Newman (Ed.), *Advanced Concrete Technology*, Butterworth-Heinemann, England.
- NZS, New Zealand Standard. 2004. “*NZS 4218: Energy Efficiency – Small Building Envelope*”. NZS, New Zealand Standard, Wellington, New Zealand.

- Park, Yoo Shin. 2005. “*The properties of the insulated lightweight stratified concrete for precast panels.*” Unpublished Report, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Popovics, S. 1973. *In proceedings of a RILEM Seminar, March 22-24, 1973, Leeds*, Vol.3; pp.6.1-1-6.1-37. The University, Leeds, England.
- Roussel. N. 2006. *A theoretical frame to study stability of fresh concrete*. Materials and Structures 39:81-91.
- Shayan, A. 1985. *Warping of Precast, White Concrete Panels*. Cement and Concrete Research 15: 245-252.
- Shi, Caijun; Wu, Yanzhong. 2005. “Mixture Proportioning and Properties of Self-Consolidating Lightweight Concrete Containing Glass Powder.” *ACI Materials Journal* 102:355-363.
- Sofi, M.; Van Deventer J.S.J.; Mendis, P.A. & Lukey, G.C. 2007. “Engineering properties of inorganic polymer concretes (IPCs).” *Cement and Concrete Research* 37:251-257.
- Sussman V. “*Lightweight plastic aggregate concrete*”. J Am concr Inst Proc 72:321-3.
- Ugural, Ansel C. and Fenster, Saul K. 2003. *Advanced Strength and Applied Elasticity*. Fourth Edition. Prentice Hall, Professional Technical Reference, Upper Saddle River, New Jersey.
- Van Deventer, J.S.J. 2002. Emerging global and local markers for geopolymers, turn potential into profit in: G.C. Lukey (Ed.), International Conference Proceedings, Melbourne, Australia, 2002, CD-ROM.
- Van Jaarsveld, J.G.S. 2000. “*The Physical and Chemical Characterisation of Fly Ash Based Geopolymers*”. PhD Thesis, Department of Chemical Engineering, The University of Melbourne, Australia.
- Yip, C.K. 2004. “*The Role of Calcium in Geopolymerisation*”, PhD Thesis, Department of Chemical and Biomolecular Engineering, The University of Melbourne, Australia.
- Zhang, Min-Hong; Li, Lian & Paramasivam, P. 2005. “*Shrinkage of High-Strength Lightweight Aggregate Concrete Exposed to Dry Environment.*” *ACI Materials Journal* 102:86-92.
- Wang, H.Y.; Tsai, K.C. 2006. “Engineering properties of lightweight aggregate concrete made from dredged silt.” *Cement & Concrete Composites* 28:481-485.

3 Materials and Mix Design

To ensure controlled segregation or stratification of concrete as well as fulfilling the technical requirements listed in Chapter 1, the mix required careful formulation and selection of materials. After basic material inspection and initial trials it was decided to carry on with two different concrete mixes.

- Pumice and perlite as lightweight materials and greywacke chips (greywacke sandstone) as normalweight material. This mix was designed to utilize local materials found in New Zealand
- Expanded glass beads and perlite as lightweight materials and slag as heavyweight material. These materials were chosen since they are easily sourced in Europe. The expanded glass beads and slag are also recycled materials, which is always becoming more important to use in concrete

After extensive testing of these mixes it was noticed that the pumice and perlite used were not consistent enough to guarantee the quality of the mix and proper stratification. The third mix was therefore developed using:

- Two grades of expanded glass beads as lightweight material and slag as heavyweight material

As well as using different materials within the mixes, two binder systems were used:

- Portland cement, a general purpose cement from Westport
- Inorganic polymers, made with fly ash and/or slag, activated with alkali and sodium silicate solutions and thermal curing

Six different mixes were therefore designed, but the mix design and some of the testing of the inorganic polymer concrete was performed by others at the University of Canterbury.¹ The author therefore focused on the design of variable density panels cast using Portland cement as a binder despite mentioning the design of inorganic polymer cement concretes.

3.1 Aggregates

Aggregates provide the bulk to concrete, typically 60-75% by volume. They reduce the cost of concrete and improve the dimensional stability of hardened concrete. The performance of aggregates in concrete is a function of the shape, texture, strength and dimensional stability of the material in the concrete. Aggregates are divided into either fine aggregate (sand) or coarse aggregate (stone).² Sand is used in concrete to provide workability, fill voids between stone particles and provide cohesion. Stones on the other hand, are added to reduce costs, provide dimensional stability and strength.

3.1.1 *Lightweight Aggregate Materials*

There are many different lightweight aggregate materials in use. In this research, pumice, perlite and expanded glass were the lightweight aggregates used.

¹ Mackechnie, J.R. 2007

² Mackechnie, J.R. 2006

3.1.1.1 Expanded Glass Beads

Expanded glass beads are made from recycled glass that cannot be utilised by the glass industry to manufacture new glass products. To produce expanded glass beads, the raw glass is ground to a fine glass powder in a large mill. After grinding the glass, some water, binding and expanding agents are added to it and the glass mixture is given its round shape in a granulating dish. The granulates are expanded in a rotating furnace ($\sim 900^{\circ}\text{C}$) which generates a fine-pored, creamy white, round granulate, entrapping minute air chambers inside. The expanded glass beads are then assorted by granular size after cooling.

Using expanded glass beads in lightweight concrete applications has many advantages such as:

- Factory made material which gives good, reliable and consistent end product
- Light but still relatively stable
- All the grains are rounded in shape
- Good heat and sound insulation properties
- Chemical resistance
- Weather resistance

In this research two granular sizes of expanded glass beads were used, 0.5-1mm and 2-4mm. These granular sizes have apparent granular densities of $470 \pm 50 \text{ kg/m}^3$ and $320 \pm 40 \text{ kg/m}^3$ and compressive strength of 2.0 and 1.4 MPa .³

3.1.1.2 Pumice

Pumice is a light, porous volcanic rock, with 90% average porosity. Pumice is formed during explosive eruptions and looks like a sponge due to its network of gas bubbles that are frozen amidst fragile volcanic glass and minerals. Volcanic gases dissolved in the liquid portion of magma expand rapidly to create a foam or froth during an explosive eruption. In pumice, the liquid part of the froth quickly solidifies to glass around the glass bubbles. All types of magma (basalt, andesite, dacite, and rhyolite) can form pumice, but it is usually light coloured varying from white, yellowish, grey, grey brown to a dull red colour. The pumice has no crystal structure and is therefore considered as glass. The amount of vesicles in the pumice is quite variable which can result in a changeful density of pumice.⁴

The pumice used in this research is mined from a quarry 50km north of Lake Taupo in New Zealand, called Atiamuri pumice after its mining location. After mining the pumice it is washed and screened to prepare it for further processing. Atiamuri pumice has relatively light weight and good hardness. Here 4-10mm pumice was used, with relative density between 1.0-1.7 or a density of $1000\text{-}1700 \text{ kg/m}^3$.⁵

Pumice is widely used as lightweight aggregate to make lightweight concrete. The abrasive nature of the pumice requires more binding media in the concrete than if made with smooth glazed surface aggregates. This increases the cost of the production and can increase shrinkage

³ Poraver. 2007

⁴ Wikipedia, *Pumice*. 2006

⁵ Inpro. 2007

potential. Abrasive aggregates also cause more stiffness in concrete due to interlock between the particles.⁶

3.1.1.3 Perlite

Perlite is a naturally occurring siliceous volcanic rock. Due to the presence of two to six percent combined water in the crude perlite rock, the perlite expands from four to twenty five times its original volume when heated to a suitable point in its softening range. In New Zealand the perlite is young age, allowing great expansion and yield nearing the maximum of up to 25 times its original volume when heated.

The crude rock pops in a manner similar to popcorn as the combined water vaporizes and creates countless tiny bubbles in the softened glassy particles when rapidly heated to above 850°C. The expanded perlite exhibits a unique, jagged interlocking structure with myriads of microscopic channels. The weight of expanded perlite can vary from 32 to 240kg/m³ depending on the manufacturing process.^{7 8}

The perlite used in this research has the following properties:⁹

- Is lightweight, with compacted density between 48 and 49.8kg/m³ and granular density of 30kg/m³ (relative density of 0.03)
- 0-3mm in diameter
- Low thermal conductivity (0.0364-0.0405W/mK)
- Enhances fire ratings since it is not combustible

Perlite is widely used as loose fill insulation in masonry construction as well as lightweight aggregate in concrete.

3.1.2 Heavy- and Normalweight Aggregate Materials

There are many different heavy- and normalweight aggregate materials in use. In this research slag and greywacke sandstone were used as heavy- and normalweight aggregates.

3.1.2.1 Slag

Slag is a by-product from smelting ore to purify metals. In nature the ore of metals such as iron, copper and lead are found in impure states where they are often oxidized and mixed in with silicates of other metals. During smelting of ores these impurities are separated from the molten metal and can be removed as slag.

Slag has many commercial uses and is often first reprocessed to separate other metals that it may contain. The remnants of the recovery are for example used in railroad track ballast, as a fertilizer, road metal or cheap and durable means of roughening sloping faces of seawalls, but air cooled slag also has good potential as aggregate in concrete.¹⁰

⁶ Ásgeirsson, Haraldur. 1994

⁷ Perlite.info. 2006

⁸ Inpro. 2007

⁹ Inpro. 2007

¹⁰ Wikipedia, *Slag*. 2006

The slag used in this research was gained from smelting iron ore, which was air cooled and crushed into aggregate at Glenbrook. Two grades of slag were used:¹¹

- Coarse slag that had 6mm nominal size, with only 1% passing through the 4750micron sieve
- Well graded fine slag (<2mm in diameter) with a fineness modulus of 3.20, with 8.2% passing the 150micron sieve

The material composition of the slag is listed in Table 3.1.¹² The slag had a relative density of 3.00 or a density of 3000kg/m³.

Table 3.1 – Material composition of the slag used in this research¹³

Material	Slag Composition [%]
Titanium, TiO ₂	35.88
Aluminium, Al ₂ O ₃	20.00
Magnesium, MgO	14.71
Calcium, CaO	13.28
Silicon, SiO ₂	10.58
Iron, Fe ₂ O ₃ T	4.52
Manganese, MnO	1.19
Sodium, Na ₂ O	0.21
Potassium, K ₂ O	0.15
Phosphorus, P ₂ O ₅	0.01

3.1.2.2 Greywacke sandstone

Greywacke is a variety of sandstone. It is generally characterized by its hardness, dark colour and poorly-sorted, angular grains of quartz, feldspar and small rock fragments set in a compact, clay-fine matrix. Greywacke is mostly grey, brown, yellow or black, dull-coloured, sandy rocks which may occur in thick or thin beds along with slates and limestone.¹⁴

New Zealand greywacke (greywacke sandstone) was formed from marine sediments that were scraped off the ocean floor by the toe of an overriding plate, crumbling the rock into folded layers.¹⁵ Most of the New Zealand greywacke consists of hard sandstone and mudstone and is less than 250 million years old.

The quality of greywacke sandstone aggregate is influenced by several factors such as:¹⁶

- Shape of the particles, being either crushed, semi crushed or rounded gravels
- The composition varies depending in the source of the sediment

¹¹ Mackechnie, J.R. 2007

¹² Scott, R.M. 2007

¹³ Scott, R.M. 2007

¹⁴ Wikipedia, *Greywacke*. 2007

¹⁵ Thornton, J. 2003:276

¹⁶ Mackechnie, J.R. 2006a

- Age of the material, with older material generally being more stable
- The degree of induration influences the hardness of the rock, with deeper levels of burial increasing the consolidation, whereas the higher temperature affects the diagenetic reaction, converting swelling clays to more stable clay minerals

In New Zealand greywacke sandstone and gravels are the most commonly used concrete aggregates. The quality of the material ranges from highly indurated greywacke sandstone to marginal gravels, contaminated with other aggregate types depending on the source. In smaller centres and throughout the South Island, the aggregate is taken from alluvial gravels whereas in all major centres it is quarried rock.¹⁷

Greywacke aggregate is relatively hard, and in New Zealand it is not considered alkali-silica reactive. The material is however occasionally infected with contaminants that can affect the performance of concrete. In this research 6mm greywacke chips from Yaldhurst were used as well as a small proportion of greywacke sand on the experimental stage. The greywacke aggregate used has a relative density of 2.65 or density of 2650kg/m³.

3.2 Binders

Binders in concrete are the hard matrix of material that fills the space between the aggregate particles and glues them together. The far most common binder used is Portland cement and therefore binders are often referred to as cement.

3.2.1 *Portland cement*

Portland cement is made by grinding calcined limestone and clay to a fine powder. When mixed with water it reacts chemically (hydrates) and hardens to form hardened cement paste. The chemical reaction between cement and water results in relatively rapid strength development under moist and temperate conditions.¹⁸

Portland cement is either made using dry process or by using wet process technology. It is common among older cement kilns to use wet process, where the ground materials are mixed with water producing slurry. In a dry process no water is added to the ground materials. Modern 'dry process' plant uses about half the energy than a 'wet process' plant does. On the other hand, mixing of the raw material is claimed to be better using a wet procedure rather than using a dry process.¹⁹ Portland cement production is a high energy process, with embodied energy between 1470 and 1110kWhr/tonne and embodied CO₂ between 1090 and 870kg/tonne depending on the production process. Where embodied energy is the total energy used in production and embodied CO₂ is the total amount of carbon dioxide produced.

The principal compounds in Portland cement clinker are 35-55% C₃S (tricalcium silicate), 20-40% C₂S (dicalcium silicate), 5-12% C₃A (tricalcium aluminate) and 4-7% C₄AF (tetracalcium aluminoferrite). The primary strength giving compounds are C₃S and C₂S that react with water to produce C₃S₂H₃ (calcium silicate hydrate) and Ca(OH)₂ (calcium hydroxide). The C₃S₂H₃ grows outward from the surfaces of unhydrated cement to form a “gel” of rigid rods and platelets that

¹⁷ Mackechnie, J.R. 2006a

¹⁸ Mackechnie J.R., 2006

¹⁹ Holcim, 2006

provides most of the strength of hardened cement paste. The Ca(OH)_2 does not contribute to strength but raises the pH of concrete pore water to above 12.5 and is involved in pozzolanic reactions.²⁰

In this research Ultracem a general purpose Portland cement from Holcim Westport was used. The ingredients in this cement are limestone (75%), sand (rock) (15%), clays (shale) (3%), iron sands (2%) and marl/shale (5%) but typical analysis of Ultracem is listed in Table 3.2. The relative density of the cement is 3.1 (density of 3100kg/m^3) and its fineness (specific surface) is $350\text{-}360\text{m}^2/\text{kg}$.

Table 3.2 – Typical analysis of Ultracem a general purpose Portland cement from Holcim Westport²¹

Typical Analysis			
SiO₂	20.7%	Na₂O	0.2%
Al₂O₃	4.1%	TiO₂	0.2%
Fe₂O₃	2.0%	Mn₂O₃	0.2%
CaO	66.1%	P₂O₅	0.1%
MgO	0.9%	Cl	0.01%
SO₃	2.5%	LOI	2.7%
K₂O	0.5%	Na Eq	0.5%
Compound Composition (on clinker component)			
Tricalcium Silicate (C₃S)			65%
Dicalcium Silicate (C₂S)			12
Tricalcium Aluminate (C₃A)			8
Tetracalcium Aluminoferrite (C₄AF)			7

3.2.2 Inorganic polymer (cement) binders

While organic polymers (plastics) are chains of carbon, hydrogen and oxygen, geopolymers (inorganic polymers or mineral polymers) are inorganic chains of aluminium, silicon and oxygen. These chains are produced from a blend of fly ash, blast furnace slag and alkali solutions that polymerize. These materials are all waste materials or by-products from other industries. Unlike Portland cement, inorganic polymers are more durable being relatively heat, fire and chemically resistant.^{22 23}

3.2.2.1 Fly Ash

Fly ash (coal combustion product) is collected by electrostatic precipitators from the flues of modern power stations that burn finely ground coal. Fly ash is a glassy phase pozzolanic material. It reacts with calcium hydroxide to form calcium silicate hydrates, which enables a denser concrete microstructure to form, due to pore refinement. As well as being used in

²⁰ Mackechnie J.R., 2006

²¹ Holcim, 2006a

²² Mackechnie J.R., 2006

²³ Fletcher Building

geopolymer concrete, fly ash is often substituted (normally 15 to 30%) for Portland cement in normal concrete. This improves workability and enhances durability by reducing the concrete's permeability.²⁴ In this research, Huntly fly ash (HFA), which is an ASTM class C fly ash (high calcium), and Gladstone fly ash (GFA), which is an ASTM class F fly ash (low calcium) were used. The compositions of these materials are listed in Table 3.3.

Table 3.3 – Oxide compositions of the fly ash used²⁵

Oxide [wt%]	HFA	GFA
NaO ₂	0.68	0.24
MgO	2.67	1.47
Al ₂ O ₃	21.04	31.05
SiO ₂	47.31	46.87
P ₂ O ₅	0.44	0.69
K ₂ O	0.51	0.51
CaO	12.70	2.97
TiO ₂	1.21	1.74
Fe ₂ O ₃	10.95	11.20
MnO	0.08	0.16
LOI	1.20	3.13

3.2.2.2 Grounded Slag

Ground granulated blast-furnace slag is a latent hydraulic binder and is a by-product from manufacturing iron and steel, that is from smelting ore. To produce ground granulated blast furnace slag (GGBS), the slag is cooled rapidly to form glassy beads, which are ground to cement fineness. As well as being used in inorganic polymer concrete, GGBS is often substituted (normally 30 to 60%) for Portland cement in concrete. This reduces the heat of hydration and improves the chloride resistance.²⁶ Here GGBS from Port Kembla, Australia was used to produce inorganic polymer concrete. Its oxide composition is listed in Table 3.4.

Table 3.4 - Oxide compositions of GGBS from Port Kembla used²⁷

Oxide [wt%]	GGBS	Oxide [wt%]	GGBS
NaO ₂	0.16	K ₂ O	0.43
MgO	6.16	CaO	41.87
Al ₂ O ₃	13.99	TiO ₂	0.55
SiO ₂	33.22	Fe ₂ O ₃	0.34
P ₂ O ₅	0.02	MnO	0.24
SO ₃	2.77	LOI	0.26

²⁴ Mackechnie J.R., 2006

²⁵ Keyte, L. & Lloyd, R. 2007

²⁶ Mackechnie J.R., 2006

²⁷ Keyte, L. & Lloyd, R. 2007

3.2.2.3 Activating chemicals for inorganic polymer binders

Pozzolanic cements such as Portland cement contain high amount of calcium that form calcium silica hydrates (CSH) for matrix formation and strength.²⁸ Inorganic polymer cements contain substantially less amount of calcium making them less reactive than pozzolanic cements. To reactivate inorganic polymer cements an alkali or alkali-silicate activating solution is used to dissolve the silica and alumina from the binder material.²⁹

Sodium silicate is a white soluble solid that dissolves in water to produce an alkaline solution. In neutral and alkaline solutions the sodium silicate is stable, but in acidic solutions it reacts with hydrogen to form silicic acid. When the silicic acid is heated and roasted it forms silica gel which is a hard, glassy substance. Sodium silicate is a compound used in cements, passive fire protection, refractories, textile and lumber processing.³⁰

Sodium hydroxide (NaOH) forms a strong alkaline solution when dissolved in a solvent such as water. Pure sodium hydroxide is a white solid but is very soluble in water with liberation of heat. Sodium hydroxide is completely ionic, containing sodium ions and hydroxide ions. The hydroxide ion makes sodium hydroxide a strong base which reacts with acids to form water and salts.³¹

Potassium hydroxide (KOH) is a metallic base. It is very alkaline and is a strong base.³²

3.3 Admixtures

Admixture is a material other than water, aggregates, hydraulic cement and fiber reinforcement that is used to enhance the performance of fresh or hardened concrete. It is added to the batch immediately, before or during mixing.³³

3.3.1 Water reducer

A water reducing admixture lowers the water required to attain a given slump; that is it reduces the water demand of the concrete. Reducing the water demand reduces the water binder ratio which generally improves the strength, impermeability and durability. Water reducers are also used to get desired slump without changing the water binder ratio. This can be done to reduce the cost of concrete by reducing the amount of cement needed or to lower the heat of hydration. Water reducers are normally divided into three groups:³⁴

- Low range (regular) – water reduction of 5-10%
- Mid range (mid range) – water reduction of 10-15%
- High range (superplasticizer) – water reduction of 15-30%

In this research MIRA 72 was used which is a mid range water reducer from Grace Construction.³⁵

²⁸ Yip, C.K. 2004

²⁹ Keyte, L. & Lloyd, R. 2007

³⁰ Wikipedia. 2007. *Sodium silicate*

³¹ Wikipedia. 2007. *Sodium hydroxide*

³² Wikipedia. 2007. *Potassium hydroxide*.

³³ Mindess, S.; Young, J. F. & Darwin, D. 2003:165

³⁴ Mindess, S.; Young, J. F.; Darwin, D. 2003:176-182

³⁵ Grace Construction Products, 2007

3.3.2 *Super-plasticiser (high range water reducer)*

Super-plasticiser is a high range water reducer that can achieve 15-30% water reduction in concrete mix while maintaining given workability.³⁶ Different admixtures have different effect on the rheological properties of concrete. While water both reduces the yield stress and plastic viscosity of concrete by providing extra lubrication of the solids, super-plasticisers significantly reduce the yield stress without significantly reducing the plastic viscosity.³⁷

Super-plasticisers used are of mainly three types:^{38 39}

- **Normal** super-plasticizer – the cement particles are given negative charge by absorbing the active substances
- **Organic** super-plasticizer – long molecules wrap themselves around the cement particles giving them a highly negative charge. The negative charge makes the cement particles repel each other
- **Polycarboxylate Ethers (PCE)** is the new generation of superplasticisers. These super-plasticisers give the cement dispersion by steric stabilization instead of electrostatic repulsion. The steric stabilization is more powerful in its effect and gives improved workability retention to the cementitious mix. The chemical structure of PCE also allows for a great degree of chemical modification which offers a range of performance that can be tailored to meet specific needs.

In this research 2 types of PCE superplasticizer were used:

- ADVA 142 from Grace Construction Products, which is a third generation polycarboxylic ether polymer⁴⁰
- Sika ViscoCrete -5-500, which is a third generation polymer-based ultra high range superplasticizer⁴¹

3.4 Mix designs

Stratified concrete is achieved by using aggregates of different densities within a moderately viscous paste that stratifies under a moderate level of vibration. To ensure controlled segregation of the concrete, the mix required careful formation and selection of materials. As mentioned before the materials used in this research were:

- Heavyweight aggregates – slag granules, greywacke sandstone
- Lightweight aggregates – expanded glass beads, perlite, pumice
- Binders – Portland cement, inorganic polymers cement made with fly ash and/or slag

After some initial trials, technical objectives for the variable density panels were developed and the thickness of the top and bottom layers estimated to get the optimum thermal performance. Roughly two thirds of the depth should be lightweight insulating concrete and the remaining third normal/heavyweight thermal storage concrete. As well as providing thermal storage, the bottom layer had to be thick enough to provide reasonable cover and bond to a light welded mesh within the layer and to provide sufficient strength for service loads and handling.

³⁶ Mindess, S.; Young, J. F.; Darwin, D. 2003:176-182

³⁷ Gaimster, R. & Dixon, N. 2003

³⁸ Neville, A.M. 1995:254-7

³⁹ Gaimster, R. & Dixon, N. 2003

⁴⁰ Grace Construction Products, 2007

⁴¹ Sika, 2005

After several initial batches the volumes were found to be incorrect. The densities of the materials were therefore checked using a coffee plunger, as described in chapter 5. The relative density of the pumice was initially assumed to be 0.7 but after several measurements the average relative density was found to be 1.16 for air dried pumice and 1.53 for damp material. As the moisture content of the pumice increased so did the relative density of the pumice while the water needed in the mix decreased. The relationship between the moisture content and the water binder ratio was not found strong enough to adjust the water binder ratio depending on the moisture content as can be seen on Figure 3.1.

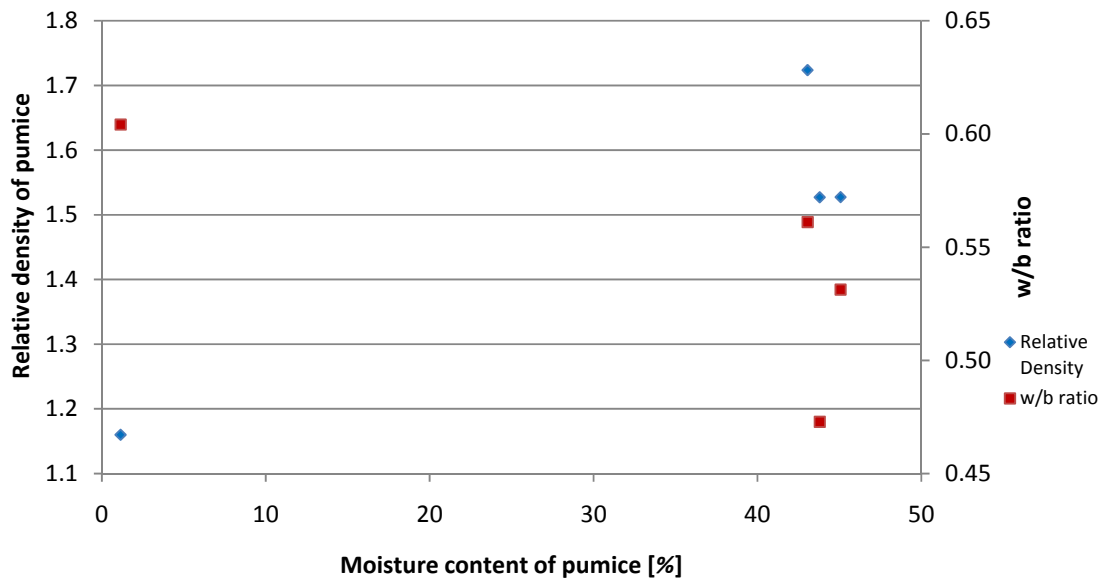


Figure 3.1 – Moisture content versus relative density and water to binder ratio; mixes PUM6, 7, 8 & 9

The measured relative density of the perlite varied from 0.21-0.34, with an average value of 0.26. As the manufacturer gives the relative density of perlite as 0.33; it was decided to use a relative density of 0.3. Inconsistency was found between delivered bags as well as within the bags as the material seemed to be heavier at the bottom.

3.4.1 *Pumice, Perlite & Greywacke Chip Mix (PUM)*

The stratification of the PUM concrete could not be assessed by its fresh properties as discussed further in chapter 6 and a proper stratification was not gained after several trials. It was therefore decided not to carry on using pumice in further research, but the best mix design developed is given in Table 3.5.

A properly stratified concrete was not gained and the mixes were highly inconsistent mainly due to the variable nature of the materials used. The poor stratification could also be related to the uneven surface of the aggregates locking each other instead of allowing the material to separate. The different material properties also made it hard to keep the lightweight layer roughly two thirds of the total height.

Table 3.5 – Final mix design for pumice, perlite and greywacke chips (PUM9)

Material	1m³
Portland Cement	300kg
Water	240L *
Fly ash	150kg
Pumice	450kg
Perlite	55kg
6mm greywacke chips	325kg
Water reducer	1.5L

Initial water to binder ratio	0.53
Final water to binder ratio	0.56
Lightweight aggregate as a proportion of volume	48%
Normalweight aggregate as a proportion of volume	12%

* Additional water increased the water to 253L

3.4.2 **Expanded Glass Beads, Perlite & Slag Mix (GB)**

The final mix design used for the GB concrete is given in Table 3.6. This mix gave well stratified samples but was too wet, having a high slump of around 600mm as well as having low yield stress. These mixes were also slightly lacking consistency, most likely due to the variable nature of the perlite. Although, this mix was used as it was guaranteed to stratify.

Table 3.6 – Final mix design for expanded glass beads, perlite and slag (GB9)

Material	1m³
Portland Cement	450kg
Water	270L
Fine slag	120kg
Coarse slag	310kg
2-4mm expanded glass beads	80kg
Perlite	58kg
Super-plasticiser	1.5L

Initial water to binder ratio	0.60
Lightweight aggregate as a proportion of volume	44%
Normalweight aggregate as a proportion of volume	14%

3.4.3 **Two Grades of Expanded Glass Beads & Slag Mix (BB)**

Due to the inconsistency found in the GB concrete, a concrete containing two grades of expanded glass beads (0.5-1mm and 2-4mm) instead of 2-4mm expanded glass beads and perlite was designed. These mixes were reasonably consistent and provided good stratification. The final mix designed is given in Table 3.7. In later mixes the water was reduced slightly when mixing, bringing the water binder ratio down to 0.60. To simplify the mixing process no chemical admixtures were used.

Table 3.7 – Final mix design for two grades of expanded glass beads and slag (BB6)

Material	1m ³
Portland Cement	450kg
Water	280L
Fine slag	120kg
Coarse slag	410kg
2-4mm expanded glass beads	94kg
0.5-1mm expanded glass beads	50kg

Initial water to binder ratio	0.62
Lightweight aggregate as a proportion of volume	40%
Normalweight aggregate as a proportion of volume	18%

3.4.4 *Inorganic polymer concrete mixes*

A series of inorganic polymer concrete mixes were developed that had similar proportions of lightweight and heavyweight aggregates to the Portland cement mixes mentioned above. The binder was made from fly ash and/or slag activated with solutions of sodium hydroxide, silicate and potassium.

A description and listing of all the concrete Portland cement mix designs can be found in the appendixes.

3.5 References

- Ásgeirsson, Haraldur. 1994. *Hekla Pumice in Lightweight Concrete*. Rannsóknarstofnun byggingariðnaðarins (The Icelandic Building Research Institute), Reykjavík, Iceland.
- Fletcher Building Limited. “*Inorganic Polymer Concrete*.” Fletcher Building, New Zealand.
- Gaimster, Rob and Dixon, Noel. 2003. Self-compacting concrete in John Newman (Ed.), *Advanced Concrete Technology*, Butterworth-Heinemann, England.
- Grace Construction Products. 2007, 19th of September. Web site: <http://www.au.graceconstruction.com>
- Holcim. 2006. *Westport Works*. Holcim (New Zealand) Ltd. Christchurch.
- Holcim. 2006a. *Ultracem*. Holcim (New Zealand) Ltd. Christchurch.
- Inpro. 2007, 30th of July. Web site: <http://www.perlite.co.nz>.
- Keyte, Louise and Lloyd, Redmond. 2007. “*Stratified Panel IPC report*” September 2007, University of Canterbury, Christchurch, New Zealand.
- Mackechnie, J.R. 2006. Lecture notes in ENCI 621, *Concrete Materials and Practice*, second semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, James R. 2006a. “Shrinkage of Concrete Containing Greywacke Sandstone Aggregate” *ACI Materials Journal* 103:390-396.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Mindess, Sidney; Young, J. Francis; Darwin, David. 2003. *Concrete*. Second Edition. Pearson Education, Upper Saddle River, New Jersey.
- Neville, A.M. 1995. “*Properties of Concrete*” Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- Perlite.info. 2006, 13th of November. Web site: <http://www.perlite.info>
- Poraver. 2007, 20th of February. Web site: <http://www.poraver.com/>
- Scott, Reece M. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Sika. 2005. “*Construction Products Catalogue*.” Issued September 2005, Sika (NZ) LTD, New Zealand.
- Thornton, J. 2003. “*Field Guide to New Zealand Geology*.” Reed Publishing, Auckland, New Zealand.
- Yip, C.K. 2004. “*The Role of Calcium in Geopolymerisation*”, PhD Thesis, Department of Chemical and Biomolecular Engineering, The University of Melbourne, Australia.
- Wikipedia. 2007, 30th of July. *Greywacke*. Web site: <http://en.wikipedia.org/wiki/Greywacke>
- Wikipedia. 2007, 5th of October. *Potassium hydroxide*. http://en.wikipedia.org/wiki/Potassium_hydroxide
- Wikipedia. 2006, 13th of November. *Pumice*. Web site: <http://en.wikipedia.org/wiki/Pumice>
- Wikipedia. 2006, 13th of November. *Slag*. Web site: <http://en.wikipedia.org/wiki/Slag>
- Wikipedia. 2007, 5th of October. *Sodium hydroxide*. Web site: http://en.wikipedia.org/wiki/Sodium_hydroxide

- Wikipedia. 2007, 5th of October. *Sodium silicate*. Web site: http://en.wikipedia.org/wiki/Sodium_silicate

3.6 Appendixes

The mix designs and the fresh properties of all the mixes cast in the developing process are listed in the tables below, followed by a brief discussion on the design process.

3.6.1 Pumice, Perlite & Greywacke Chip Mix

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fly Ash [kg]	Pum- ice [kg]	Per- lite [kg]	6mm Grey- wacke Chip [kg]	Sand [kg]	Super- Plasti- ciser	Water re- ducer	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	τ_0 [Pa]	μ [Pas]	Sepa- ration [%]	Average Stratifi- cation [%]	Visual stratifi- cation
09.11.06	TS2	300	200 (140)	150	240	30 (34)	480	0	2.5	0	0.44 (0.31)	46 (50)	18 (19)	620	0	108	0		4 top cylinders (Structural) 4 bottom cyl (Structural) 3 top shrinkage prism 3 bottom shrinkage prism
15.11.06	TS3	300	200	150	240	30	480	0	2.5	0	0.44	46	18.0	460	69	23.8	9		4 top cylinders (Structural) 4 bottom cyl (Structural) 3 top shrinkage prism 3 bottom shrinkage prism
22.11.06	TS5	300	210	150	240	30	445	0	2.5	0	0.47	46	17	610	4	5.2	7	-	Moderate
27.11.06	TS8	300	210	150	226	35	445	0	2.5 (1.5)	0	0.47	46	17	560	22	9.8	12	-	Moderate
28.11.06	TS9	300	200	150	230	35	350	100	2.5 (1.6)	0	0.44	47	17	530	43	14.1	11	-	Poor
29.11.06	TS10	300	200	150	230	35	350	100	2.50	0	0.44	47	17	570	40	11.5	9	-	Poor
06.12.06	Pan 2 100L	300	210	150	226	35	445	0	2.3 (0.44)	0	0.47	46	17	595	19 (32)	8.2 (10.4)	9 (10)	Exposed Panel	
06.12.06	Pan 2 20L	300	210	150	226	35	445	0	2.3 (0.44)	0	0.47	46	17		40	14.9	8		
24.01.07	PU1	300	210	150	226	35	445	0	0.5	0	0.47	46	17	550	59	7	-1		4 top cylinders (big) (Structural) 4 bottom cyl (big) (Structural) 3 top shrinkage prism 3 bottom shrinkage prism

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fly Ash [kg]	Pum- ice [kg]	Per- lite [kg]	6mm Grey- wacke Chip [kg]	Sand [kg]	Super- Plasti- ciser	Water re- ducer	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	T ₀ [Pa]	μ [Pas]	Sepa- ration [%]	Average Stratifi- cation [%]	Visual stratifi- cation
30.01.07	PU2	300	210	150	226	35	445	0	0.5	0	0.47	46	17	580	14	7.7	4	4 top cylinders (big) (Structural) 4 bottom cyl (big) (Structural) 3 top shrinkage prism 3 bottom shrinkage prism	
15.02.07	PU3	300	210	150	226	35	445	0	0.5 (0.75)	0	0.47	46	17	650	3	8.3	5	2x Beam 470x120x120 Beam 530x150x120	
06.03.07	PUM1	300	210 (227)	150	240	39.5	445	0	0.5 (1.83)	0	0.47	46	17	640	0	20.1	15	7.3	Poor
09.03.07	PUM2	300	225 (315)	150	325	45	490	0	1.5	0	0.50 (0.70)	43	19	430	73	16.6	12	7.6	Poor
11.03.07	PUM3	300	300	150	270	40	460	0	1.5	0	0.67	37	17	700	238	7	2	11.3	Mod
12.03.07	PUM4	300	270	150	290	42	480	0	1.5	0	0.60	39	18	510	40	44	8	11.1	Mod
27.03.07	PUM5	350	270	150	300	(43) 57.5	400	0	2 (1.4)	0	0.54	(40) 43	15 (14)	605	3	22.3	13	16	Good
28.03.07	PUM6	330	240 (290)	150	310	55	370	0	1.5 (2)	0	0.50 (0.60)	45 (43)	14 (13)	640	11	23.4	20	12.8	Mod/ Good
03.04.07	PUM7	330	240 (227)	150	310	55	370	0	1.5	0	0.50 (0.47)	45	14	660	691	42	1	14.9	Mod/ Good
10.04.07	PUM8	330	255 (235)	150	400	55	400	0	0	1.5	0.53 (0.49)	44	15	500	34	13	13	10.5	Mod
11.04.07	PUM9	300	(253) 240	150	450	55	325	0	0	1.5	0.56 (0.53)	48	12	500	43	17.4	12	13.1	Mod/ Good
16.04.07	PUM10	250	220	150	560	55	325	0	0	1.5	0.55	51	12	495	31	19.4	12	9.7	Poor
20.04.07	PUM11	250	220	150	560	55	325	0	2	0	0.55	51	12	620	1749/ 846	17.5/ 18.3	1/ 2	7.5	Poor

3.6.2 Expanded Glass Beads, Perlite & Slag Mix

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fine Slag [kg]	Coarse Slag [kg]	Per- lite [kg]	Exp. Glass beads [kg]	Super Plasti- ciser	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	τ_0 [Pa]	μ [Pa]	Sepa- ration [%]	Stratifi- cation 30sec [%]	Stratifi- cation 45sec [%]	Stratifi- cation
08.11.06	TS1	450	(300) 290	100	480	50	50	0	(0.67) 0.64	37	19	540	18	7.4	14	4 top cylinders (Structural) 4 bottom cylinders (Structural) 3 top shrinkage prism 3 bottom shrinkage prism		
22.11.06	TS4	415	(275) 285	100	400	65	50	0	(0.66) 0.69	43	17	480	22	11.1	18	-	-	Good
27.11.06	TS7	400	(280) 285	150	350	65	50	0	(0.70) 0.72	43	17	460	30	15	15	-	-	Good
28.11.06	TS6	400	280	200	300	65	50	0	0.7	43	17	460	46	16.4	17	-	-	Good
07.12.06	Pan 1 100L	415	(275) 277	100	400	65	50	0	(0.66) 0.67	43	17	530	32	5.8	3	Exposed Panel		
07.12.06	Pan 1 20L	415	275	100	400	65	50	0	0.66	43	17		56	22.4	11			
23.01.07	GL1	415	(275) 283	100	400	65	50	0	(0.66) 0.68	43	17	(460) 490	(70) 48	(14.7) 10.4	(12) 13	4 top cylinders (Structural) 4 bottom cylinders (Structural) 3 top shrinkage prism 3 bottom shrinkage prism		
14.02.07	GL2	415	(275) 291	100	400	65	50	0	(0.66) 0.7	43	17	505	53	10.7	13	4 top cylinders (Structural) 3 bottom cylinders (Structural) Beam 470x120x120 Beam 530x150x120		
06.03.07	GB1	450	(290) 303	120	460	68	50	0	(0.64) 0.67	37	19	450	57	13.3	11	13.8	18.5	Moderate
14.03.07	GB2	450	300	120	460	62	50	0	0.67	36	19	470	40	13.9	14	19.4	21.0	Moderate
15.03.07	GB3	450	300	120	350	62	62	0	0.67	39	16	420	55	17.8	13	21.3	22.0	Moderate
19.03.07	GB4	450	(306) 314	120	350	60	62	0	(0.68) 0.70	39	16	440	38	14	16	19.4	23.3	Moderate / Good
20.03.07	GB5	450	(305) 310	120	350	55	68	0	(0.68) 0.69	40	16	425	58	15.1	11	22.3	24.0	Moderate / Good

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fine Slag [kg]	Coarse Slag [kg]	Per- lite [kg]	Exp. Glass beads [kg]	Super Plasti- ciser	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	T ₀ [Pa]	μ [Pas]	Sepa- ration [%]	Stratifi- cation 30sec [%]	Stratifi- cation 45sec [%]	Stratifi- cation
22.03.07	GB6	450	270	120	350	55	75	1.5	0.60	42	17	600	15	13.2	8	23.4	26.1	Good
23.03.07	GB7	450	270	120	350	55	75	1.0	0.60	42	17	485	44	35.2	14	17.9	25.0	Moderate
30.03.07	GB8	450	(260) 270	120	320	60	80	1.5	(0.58) 0.60	45	15	(545) 595	(555) 27	(66.3) 8.8	(19) -33	24.0	26.1	Good
12.04.07	GB9	450	270	120	310	58	80	1.5	0.60	44	14	595	-31	34.6	29	20.7	27.0	Good
16.04.07	GB10	450	270	120	310	58	80	1.5	0.60	44	14	590	-21	30.1	26	4 top cylinders (big) (Structural)		
																4 bottom cyl (big) (Structural)		
19.04.07	GBP1	450	(270) 281	120	310	58	80	1.5	(0.60) 0.63	44	14	580	2	27.5	13	Panel vibrated for 15seconds		
19.04.07	GBP2	450	270	120	310	58	80	1.5	0.60	44	14	595	56	10.1	-36	Panel vibrated for 45seconds		
23.04.07	GBP3	450	270	120	310	58	80	1.5	0.6	44	14	600	76	2.4	-37	Panel vibrated for 30seconds		

3.6.3 Two Grades of Expanded Glass Beads & Slag Mix

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fine Slag [kg]	Coarse Slag [kg]	Exp. Gl.B. 2- 4mm [kg]	Exp. Gl.B. 0.5- 1mm [kg]	Super Plasti- ciser	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	T ₀ [Pa]	μ [Pas]	Sepa- ration [%]	Stratifi- cation 30sec [%]	Stratifi- cation 45sec [%]	Stratifi- cation
05.06 07	BB1	450	225 (245)	120	390	100	70	1.5	0.50 (0.54)	46	17	460	176	15.2	2	8.9	11.6	Poor
12.06 07	BB2	450	250 (240)	120	390	112	40	1.5	0.56 (0.53)	44	17	500	106	13.3	3	-	15.2	Poor
15.06 07	BB3	450	260	120	380	110	40 (55)	1.5	0.58	43 (45)	17 (16)	525	75	18.4	2	-	-	Poor
18.06 07	BB4	450	260 (290)	120	380	100	55	0	0.58 (0.64)	43	17	455	26	8.6	7	22.0	26.5	Good

DATE	MIX	Ce- ment [kg]	Wat- er [L]	Fine Slag [kg]	Coarse Slag [kg]	Exp. G.I.B. 2- 4mm [kg]	Exp. G.I.B. 0.5- 1mm [kg]	Super Plasti- ciser	w/b ratio	Light- weight [%]	Heavy- weight [%]	Slump flow [mm]	T ₀ [Pa]	μ [Pa·s]	Sepa- ration [%]	Stratifi- cation 30sec [%]	Stratifi- cation 45sec [%]	Stratifi- cation
19.06 07	BB5	450	280	120	380	96	52	0	0.62	41	17	440	33	7.4	-3	27.7	28.8	Good
21.06 07	BB6	450	280	120	410	94	50	0	0.62	40	18	480	28	8.8	5	27.0	26.9	Good
27.06 07	BB7	450	280	120	410	94	50	0	0.62	40	18	470	26	8.9	11	3 top shrinkage prism 3 bottom shrinkage prism		
12.07 07	BB8	450	280	120	410	94	50	0	0.62	40	18	480	81	-2.2	-28	Panel vibrated for 15sec		
12.07 07	BB9	450	280	120	410	94	50	0	0.62	40	18	470	49	2.4	-16	Panel vibrated for 45sec		
24.07 07	BB10	450	280	120	410	94	50	0	0.62	40	18	465	51	1.9	-27	4 top cylinders (Structural) 4 bottom cylinders (Structural)		
26.07 07	BB11	450	280 (268)	120	410	94	50	0	0.62 (0.59)	40	18	475	27	8.5	6	2x30sec cylinders (durability) 2x45sec cylinders (durability) 2x30sec big cylinders (thermal) Beam 1350x80x120 vibr. for 45sec		
30.07 07	BB12	450	280 (275)	120	410	94	50	0	0.62 (0.61)	40	18	475	32	7.1	5	2x45sec big cylinders (thermal) Beam 1350x80x120 vibr. for 30sec		
31.07 07	BB13	450	280 (265)	120	410	94	50	0	0.62 (0.59)	40	18	465	29	13.1	16	Beam 1350x80x120 vibr. for 15sec		
13.09 07	BB shrink	450	280 (270)	120	410	94	50	0	0.62 (0.60)	40	18	475	26	6	-2	3 top shrinkage prism 3 bottom shrinkage prism		

3.6.4 *Further description of the mix design process*

3.6.4.1 Pumice, Perlite & Greywacke Chip Mix (PUM)

PUM1 – A relative density of 0.33 for perlite and 0.7 for pumice was used. As the pumice was air dried, a large amount of excess water and super-plasticiser was needed to get good workability with a slump flow over 500mm. The water binder ratio was increased from being 0.47 to 0.50 and the amount of superplasticizer was increased from being 0.5 L/m³ to 1.83L/m³. The mix had a slump flow which was too high and poor rheology giving poor stratification (Figure 3.2).

PUM2 – The water binder ratio was 0.50 and 1.5 L/m³ of superplasticizer was used. The amount of pumice was increased by weight but not by volume (higher relative density), while the amount of perlite was increased both in weight and volume. The mix was too dry providing poor workability. Additional water was added, increasing the water binder ratio to 0.7. Despite adding water, the workability was not good with a slump flow of 430mm providing poor to moderate stratification (Figure 3.3).

PUM3 – The amount of aggregates was decreased as the amount of water was increased, setting the water binder ratio to 0.67 and 1.5L/m³ of superplasticizer were used. A lot of excess water was in the mix which started segregating in the mixer. The cylinders cast had a moderate stratification, with the paste segregating from the aggregates as well as trapped pumice within the structural layer (Figure 3.4).

PUM4 – The water binder ratio was reduced to 0.6 (270 L/m³) in an attempt to achieve a flowable mix without having it segregating in the mixer. The mix ended having a slump flow of 510mm, no segregation in the mixer and moderate stratification. The paste was not segregating as much from the aggregates but there was still trapped lightweight material within the structural layer (Figure 3.5).

PUM5 – As high water content increases the shrinkage potential of concrete, the water was decreased and the super-plasticizer dosage increased. As the structural layer was higher than one third in the previous mix, the amount of lightweight material was increased and the normalweight material decreased. Despite not using all the superplasticizer, some excess water was observed and there was some indication of segregation within the mixer due to 33% moisture content of the pumice. To dry up the mix, extra perlite was added. This mix provided well stratified cylinders, despite still having some trapped lightweight material within the structural layer increasing its thickness (Figure 3.6).

PUM6 – The water binder ratio was decreased to 0.5, 1.5L/m³ of superplasticizer and well dried pumice was used. As the structural layer was still too high, the volume of lightweight material was increased. After adding 1L of water, increasing the water binder ratio to 0.6, the slump flow was only 450mm. Additional superplasticizer increased the dosage to 2L/m³. This changed the fresh properties completely, increasing the slump flow to 640mm. The rheological properties were well within the acceptable range with a yield shear stress of 11Pa and plastic viscosity of 23.4Pas. The mix provided moderate segregation after 45seconds and moderate to good segregation after 60seconds (Figure 3.7).

PUM7 – Using damp material the water binder ratio was set at 0.5. Despite not adding all the water into the mix, the mix was too wet and the rheological properties were way out of range indicating a really sticky mix. Such a sticky mix was not expected to segregate at all, but some stratification was experienced providing moderately stratified cylinders (Figure 3.8). After casting this mix the relative density of damped pumice was adopted and increased to 1.53.

PUM8 – Trying to get a more consistent mix, a regular water reducer was used instead of superplasticizer. Due to poor workability, water was added increasing the water binder ratio to 0.53. Despite having a slump flow of 500mm and other rheological properties within desired range the cylinders were only moderately segregated (Figure 3.9).

PUM9 – As the mix was still lacking lightweight materials; the amount of pumice was increased and the amount of greywacke chips and cement decreased. After adding 250ml of water the slump flow had increased to 500mm and the rheological properties were within acceptable range. The mix only provided moderate stratification having some trapped pumice within the structural layer but it is obvious that 48% of the volume is not lightweight material (Figure 3.10). The density of the pumice was now found to be 1.72 on average explaining the lack of lightweight material.

PUM10 – The relative density of the pumice was set as 1.70 and the amount of lightweight material was increased as the cement was decreased. Despite having good fresh properties the mix provided poorly stratified cylinders (Figure 3.11). This behaviour of the mix is hard to explain but might be related to the uneven surface of the aggregates locking each other instead of allowing the lightweight material to float up to the surface.

PUM11 – A new superplasticizer was introduced (Sika ViscoCrete-5-500), one final mix was therefore cast before giving up on the pumice due to its poor consistency and stratification. The same mix design was used as for PUM10, except 2L/m³ of superplasticizer were used instead of 1.5L/m³ of water reducer. The slump flow was 620mm and the rheological properties were completely out of range with a yield shear stress of 1749Pa. Having such a high yield shear stress provided poorly stratified cylinders as expected.

The fresh properties of mixes PUM8, PUM9 and PUM10 indicated that more consistency could be gained by using water reducer instead of super-plasticiser. Despite being able to guarantee the fresh properties a proper stratification could not be guaranteed.

Mixes PUM6, PUM7 and PUM9 were showing better stratification than mixes PUM10 and PUM11. Mixes PUM6, PUM7 and PUM11 were highly flowable with a slump flow over 600mm while mixes PUM9 and PUM10 had slump flow around 500mm. However, the slump flow did not seem to matter in terms of stratification of the cylinders. In mix PUM10 the rheological properties were within the desired range whereas PUM7 was far outside that range. But, PUM10 was poorly stratified while PUM7 gave moderately stratified cylinders. It was hard to assess the potential for stratification from the fresh properties and therefore it was decided not to carry on using pumice in further research.



Figure 3.2 - Cylinders cast from mix PUM1



Figure 3.3 - Cylinders cast from mix PUM2



Figure 3.4 - Cylinders cast from mix PUM3



Figure 3.5 - Cylinders cast from mix PUM4



Figure 3.6 - Cylinders cast from mix PUM5



Figure 3.7 - Cylinders cast from mix PUM6



Figure 3.8 - Cylinders cast from mix PUM7



Figure 3.9 - Cylinders cast from mix PUM8

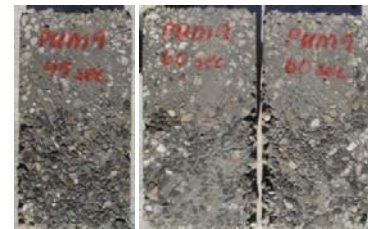


Figure 3.10 - Cylinders cast from mix PUM9



Figure 3.11 - Cylinders cast from mix PUM10

3.6.4.2 Expanded Glass Beads, Perlite & Slag Mix (GB)

GB1 – After adding some water, increasing the water binder ratio to 0.67, the mix provided moderately stratified cylinders (Figure 3.12).

GB2 – The water to binder ratio was set at 0.67, while the amount of perlite was decreased. The mix gave moderately stratified cylinders but the amount of heavyweight material was too high, having more than one third of the height as structural concrete (Figure 3.13).

GB3 – The amount of expanded glass beads was increased and the amount of slag decreased. As the mix was too sticky only moderately stratified cylinders were gained with some trapped lightweight material within the structural layer. Due to the trapped material it is hard to estimate if the structural layer is one third of the total height (Figure 3.14).

GB4 – To increase the workability some water was added as the amount of perlite was decreased. By decreasing the amount of perlite the workability should have increased even further as it takes up a lot of water. The mix was within the desired range of rheological properties and gave moderately to well stratified cylinders with some trapped lightweight material, (Figure 3.15). The material seems to be trapped on the sides of the cylinders indicating some drag effects by the mould.

GB5 – To increase the workability some perlite was exchanged by expanded glass beads. The mix had a slump flow of 425mm, yield shear stress of 58Pa and plastic viscosity of 15.1Pas. The slump flow was a bit too low and the yield shear stress slightly too high. The cylinders were moderately to well stratified (Figure 3.16).

GB6 – As high water to binder ratio increases the shrinkage it was undesirable to increase the workability by adding more water. Some superplasticizer was therefore used and the water reduced. After adding 0.5L/m³ of superplasticizer the yield shear stress was too high and the slump too low. After adding 1.5L/m³ the mix was too flowable and started segregating within the mixer and when vibrated the paste separated from the aggregates (Figure 3.17).

GB7 – Decreasing the amount of superplasticizer to 1L/m³ did not give sufficient results. The plastic viscosity was 35.2Pas while the yield shear stress was 44Pa and the slump flow 485mm. This mix only produced cylinders with moderate stratification (Figure 3.18).

GB8 – The superplasticizer dosage was increased by 0.5L/m³ and the amount of lightweight material was also increased too get the right thickness of the layers. After adding some water the mix provided well stratified cylinders with the bottom layer about one third of the total height (Figure 3.19).

GB9 – In an attempt to get the final mix, the amount of light- and heavyweight material was decreased while the water was increased, setting the water binder ratio at 0.60 again. The fresh properties of the mix were a bit out of range with a slump flow of 595mm, yield shear stress of 0Pa and a plastic viscosity of 34.6Pas. Despite this, the mix provided well stratified cylinders (Figure 3.20) so it was decided to carry on with the structural and serviceability testing using this mix since this mix should definitely stratify and therefore be suitable for testing.



Figure 3.12 – Cylinders cast from mix GB1



Figure 3.17 - Cylinders cast from mix GB6

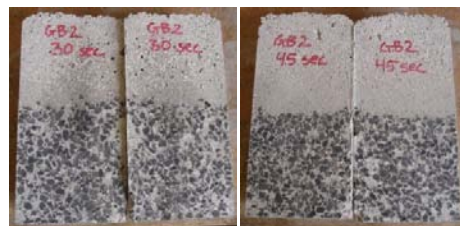


Figure 3.13 - Cylinders cast from mix GB2



Figure 3.18 - Cylinders cast from mix GB7



Figure 3.14 - Cylinders cast from mix GB3



Figure 3.19 - Cylinders cast from mix GB8



Figure 3.15 - Cylinders cast from mix GB4



Figure 3.20 - Cylinders cast from mix GB9



Figure 3.16 - Cylinders cast from mix GB5

3.6.4.3 Two Grades of Expanded Glass Beads & Slag Mix (BB)

Due to the unstable nature of the expanded glass beads, perlite and slag mix, a mix containing two grades of expanded glass beads (0.5-1mm and 2-4mm) and slag was designed.

BB1, BB2 and BB3 – When mixing these mixes the mixer was out of adjustment. The mixer was not scraping the bottom of the pan and therefore not mixing the paste into the aggregates. The cylinders had a poor stratification as can be seen on Figure 3.21.

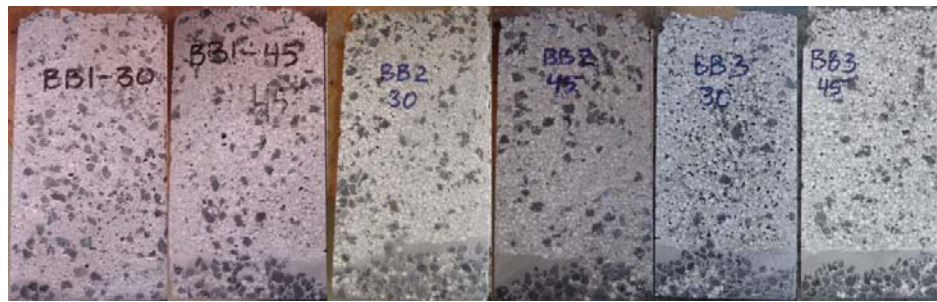


Figure 3.21 - Cylinders cast from mix BB1, BB2 and BB3 vibrated for 30 and 45seconds

BB4 – Trying to simplify the mix, the superplasticizer was replaced by some additional water. After adding some extra water increasing the water binder ratio to 0.64 the mix had good fresh properties with a slump flow of 455mm, yield shear stress of 26Pa and a plastic viscosity of 8.6Pas. The cylinders were well stratified but were lacking heavyweight material (Figure 3.22).

BB5 – The volume of the lightweight material was decreased and the amount of slag increased. The water binder ratio was set at 0.62. The mix had good fresh properties and stratified well but the proportion of lightweight material was still too high leaving less than one third of the total height as a structural layer (Figure 3.23).

BB6 – The volume of the lightweight material was decreased and the heavyweight material increased even further. The mix had good fresh properties, the cylinders were well stratified and the structural layer was approximately one third of the total height, Figure 3.24. It was decided to carry on with the structural and serviceability testing using this mix.

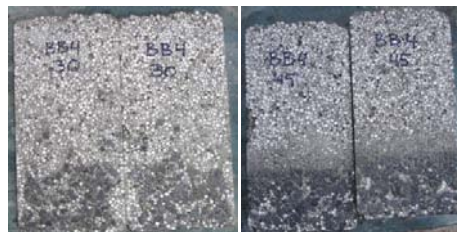


Figure 3.22 - Cylinders cast from mix BB4



Figure 3.23 - Cylinders cast from mix BB5



Figure 3.24 - Cylinders cast from mix BB6

4 Methodology

Test methods for basic testing of concrete are well known, but specific techniques such as measuring warping have not been fully developed. Test methods used in this research are described in the following chapter. Properties that the variable density concrete was tested for included:

- Density of the lightweight material
- Fresh properties
- Stratification in the fresh and hardened state
- Hardened properties
- Durability performance
- Shrinkage and warping
- Thermal properties

As well as describing these test procedures the sample preparation is described.

4.1 Density of lightweight material

To find the density of lightweight materials, a 1000ml coffee plunger was used. The granular density was determined by putting 500ml of water into the coffee plunger, and then adding approximately 400ml of weighed material. After pressing the material lightly into the water the volume was read. The granular density could then be found by using following equation:

$$\rho = \frac{m}{V - (V_s + 500)}$$

Where:

- ρ is the granular density
- m is the weight of the material
- V is the total volume of the water and the material
- V_s is the volume of the plunger or 15ml



Figure 4.1 – The coffee plunger used to measure density of lightweight material and pumice being tested

This is a similar method to that used by Poraver.¹ As a control test, the relative density of the 2-4mm expanded glass beads was measured, as it is a manufactured material that has high consistency in its material properties. The pumice and the perlite are natural materials that do not have as consistent material properties and therefore could not have been used to perform a control test. The relative density of the expanded glass beads was found to be 0.32, which is the same value as provided by the producer.

4.2 Fresh properties

The fresh properties recorded were the slump flow, plastic viscosity, yield shear stress and separation. The slump was determined according to NZS 3112: Part 1: 1986² and the rheology by using a BML-Viscometer³.

4.2.1 Slump flow

In this research a conventional slump flow test (spread test) was performed, commonly used for high slump or self compacting concrete. The test uses:

- A slump cone that is 300mm high, 200mm in diameter at the top and 100mm at the bottom
- A flat, smooth surfaced, non-absorbent 800x800mm plate as base. The base has to be level and free of vibration
- A measuring tape

The concrete is placed in the cone with minimum possible segregation or compaction after mixing. The cone is then quickly lifted up, over 2seconds, without tilting and held steady. The diameter of the concrete disc is measured approximately 10seconds after lifting the cone or when the concrete stops flowing. The diameter is measured across two diameters at right angles to one another, and the average of these two measurements reported as the spread of the concrete to the nearest 10mm.⁴

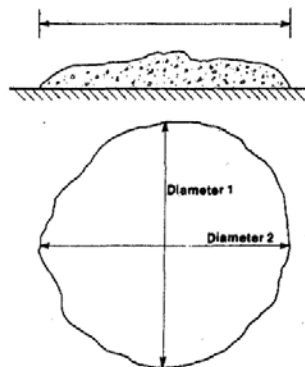


Figure 4.2 – Slump flow measurement⁵

¹ Poraver. 2007

² NZS 3112, Part 1. 1986a

³ ConTec. 2006

⁴ NZS 3112, Part 1. 1986a

⁵ CCANZ, 2006. p. IB 50

4.2.2 Rheology

The rheological properties of the mixes were assessed by using a BML-Viscometer. The BML-Viscometer is a coaxial cylinder viscometer for coarse particle suspension that measures the rheological properties of cement paste, mortar and concrete with 80mm slump or higher.⁶ The BML-Viscometer is able to measure a shear stress between 0.5 and 2000Pa; that is from a highly flowable mortar to a low workable concrete.⁷

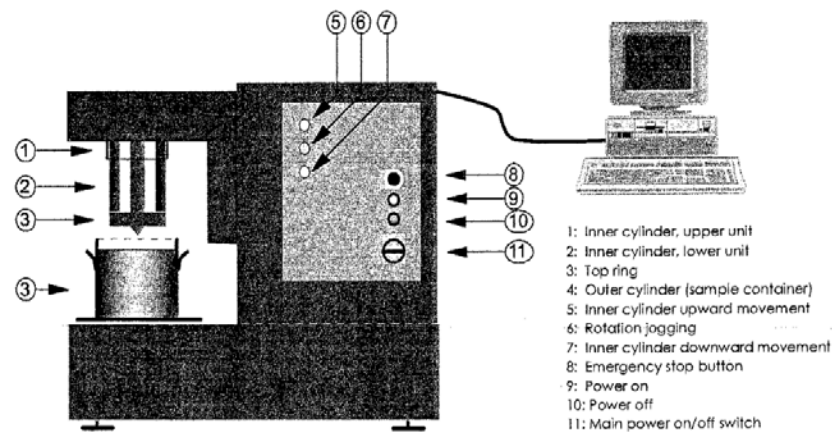


Figure 4.3 – Diagram of the BML-Viscometer⁸

The rheological properties are described by the fundamental parameters in the Bingham model, the yield value and the plastic viscosity, with the relationship:

$$\text{Torque} = G + H \times \text{Speed}$$

Where:

- G is the flow resistance which is a measure of the force necessary to start movement of the concrete
- H is the viscosity factor which is a measure of the resistance of the concrete against an increased speed of movement

The torque produced on a stationary inner cylinder while the outer cylinder is rotating at various speeds is measured to be able to determine the values of G and H.⁹ The viscometer also indicates the segregation factor, which can be considered as the change in viscosity during testing.¹⁰

A computer application called FRESH, controls the testing process and plots a torque-speed diagram. By using linear regression analysis, the G and H values can be calculated, but other rheological values gained are:¹¹

- Regression coefficient (r)
- 90% confidential intervals for G and H

⁶ ConTec. 2006

⁷ ConTec Ltd. 2003

⁸ ConTec Ltd. 2003. p.18

⁹ ConTec Ltd. 2003

¹⁰ ConTec. 2006

¹¹ ConTec Ltd. 2003

- Segregation coefficient (Seg) – is the relative change in slope (or viscosity) during a performance of a test, found by following equation but the parameters are described on Figure 4.4.

$$Seg = \frac{H-H'}{H} \cdot 100\%$$

- Yield value (τ_0) – is caused by inter-particle forces within concrete, such that the material appears stiff until these links are broken by shear
- Plastic viscosity (μ) – is the resistance to flow once the yield stress has been exceeded
- Plug Speed (Np)

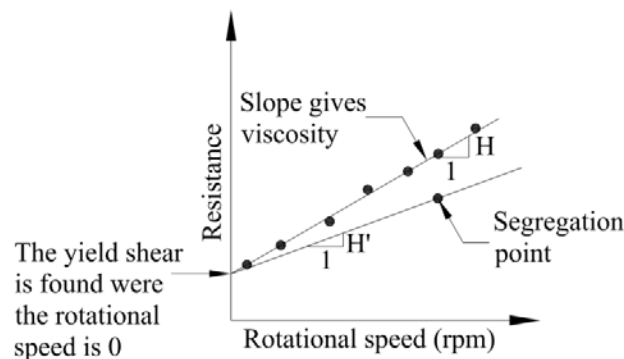


Figure 4.4 – Typical torque-speed diagram gained from the BML-Viscometer¹²

In this research, the main focus was on the yield value and the plastic viscosity, but the segregation point was also recorded.

To ensure adequate accuracy and speed of testing, the apparatus is fully automated in an attempt to minimise the influence of operator bias. The procedure is therefore simple; after situating the inner cylinders, concrete is put into the sample container and the test is started. A standard test begins at the highest speed and is reduced stepwise until the lowest speed is reached. The total testing time is about 3-4 minutes and during this period the concrete is exposed to direct movement for only 75 seconds in a standard test procedure.¹³



Figure 4.5 – BML Viscometer

¹² ConTec Ltd. 2003

¹³ ConTec. 2006

4.3 Stratification

The amount of stratification is affected by the intensity and time of vibration. Assessing the amount of stratification is essential in both hardened and fresh state. In the fresh state, the penetration depth was measured, whereas the stratification was assessed visually and by finding the centre of mass in the hardened state. The stratification in the hardened state can also be assessed by using photo analysis; this was not done here as finding the centre of mass gave a good indication of the amount of stratification. In the fresh state, a wet sieving method can also be used; this was not performed in this research as it is time consuming and does not allow any further use of the concrete.

4.3.1 *Different vibration times and vibration frequency*

Stratification of concrete is dependent on the vibration intensity. Trying to optimise the vibration intensity, different intensities were applied to concrete cylinders over the same amount of time. Intensities of 2500, 3000 and 3500*rsp* were applied over 30*seconds*. As the stratification is also depended on the vibration time, the vibration time was also optimised by vibrating some samples for 15, 30, 45, 60 and 90*seconds*, at an intensity of 3000*rsp*. After at least 24*hours*, curing the cylinders were cut and the stratification rated.

4.3.2 *Wet sieving method*

A wet sieving method had been used previously to estimate the degree of stratification of fresh concrete.¹⁴ The wet sieve used a washing-out test which consisted of casting and stratifying a unit volume of concrete and then measuring the relative proportion and weight of coarse aggregate at different depths through the section as shown on Figure 4.6.

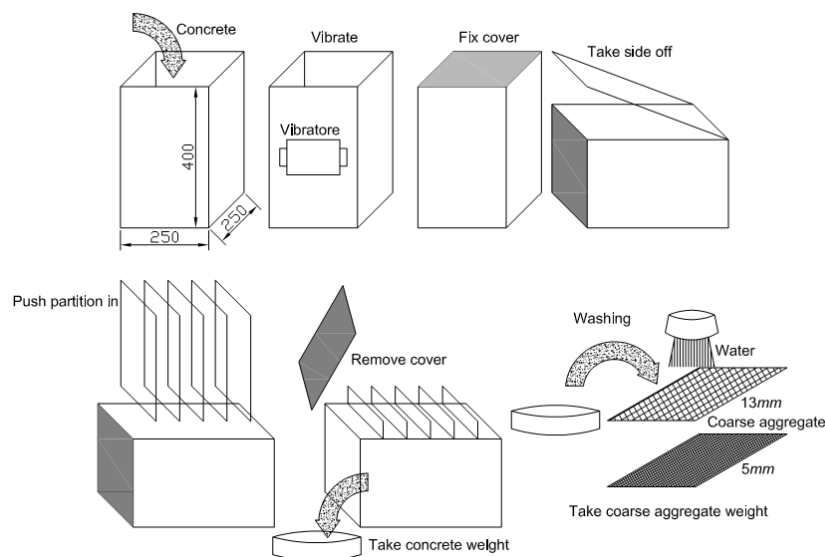


Figure 4.6 – Configuration of the wet sieve method used¹⁵

¹⁴ Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

¹⁵ Park, Y.S., 2006

The test measures the segregation coefficient (SC) of concrete listed in Table 4.1.

Table 4.1 – Stratification rating compared to the segregation coefficient¹⁶

Stratification rating	Washout index (SC)
None	0.0 - 0.1
Slight	0.1 - 0.2
Mild	0.2 - 0.3
Moderate	0.3 - 0.4
Good	0.4 - 0.5
Excellent	> 0.50

This method gave good results but was too time consuming and the concrete cannot be used to prepare other samples, as mentioned before.

4.3.3 Penetration depth method

In previous research different variations of penetration depth tests have been used to assess the segregation of self compacting concrete (SCC). Usually the penetration apparatus is placed on the upper surface of the concrete sample so that the penetration cylinder can penetrate freely into the concrete. After a certain time period the penetration depth is recorded. The penetration depth is usually measured at minimum three locations, and the average of these measurements recorded as the penetration depth. A typical arrangement of this test procedure can be viewed on Figure 4.7.¹⁷

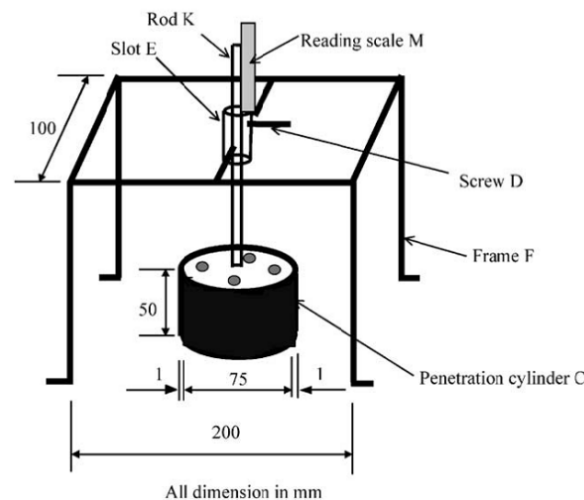


Figure 4.7 – Penetration apparatus used for rapid testing of segregation resistance of SCC¹⁸

In recent research the previous test has been modified as shown on Figure 4.8. The modified version consists of four penetration heads mounted on a steel frame instead of one. The average penetration depth of the heads is recorded after allowing them to penetrate under its self weight.¹⁹

¹⁶ Park, Y.S., 2006

¹⁷ Bui, V.K.; Montgomery, D.; Hinczak, I. & Turner, K. 2002

¹⁸ Bui, V.K.; Montgomery, D.; Hinczak, I. & Turner, K. 2002

¹⁹ El-Chabib, Hassan and Nehdi, Moncef. 2006

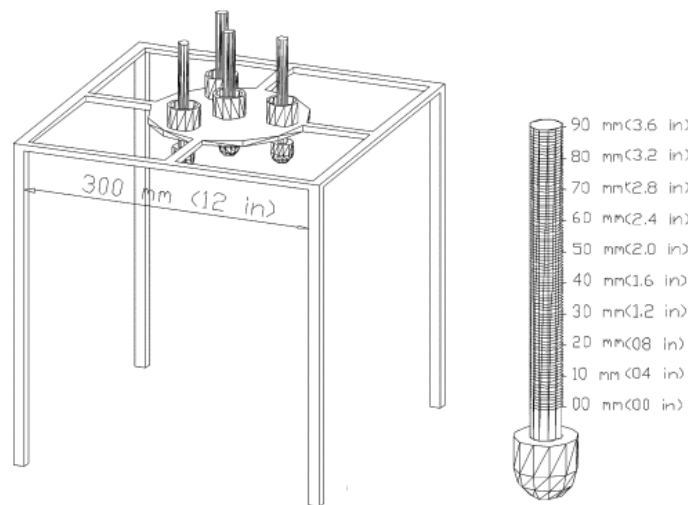


Figure 4.8 – Modified penetration depth apparatus²⁰

In this research a steel rod, 304mm long, 10mm in diameter and 183gr, was placed at the centre on the upper surface of the 100mm cylinders being cast, as shown on Figure 4.9. The rod was allowed to penetrate under its self weight and the penetration depth recorded. A special apparatus was not built to control the test further and to gain better consistency in the results. Only a limited amount of trials were undertaken with this technique and no attempt was made to use differing diameters or weights of penetrating rods.

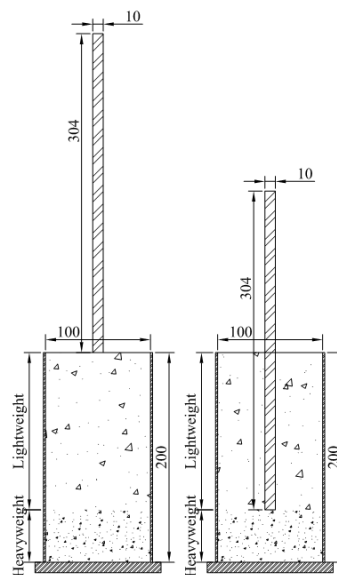


Figure 4.9 – Schematic figure of the penetration depth test

²⁰ El-Chabib, Hassan and Nehdi, Moncef. 2006

4.3.4 Centre of mass of stratified cylinders

The stratified cylinders were cured for at least 24hours when a longitudinal cut was made. The centre of mass was found by using the apparatus shown on Figure 4.10.

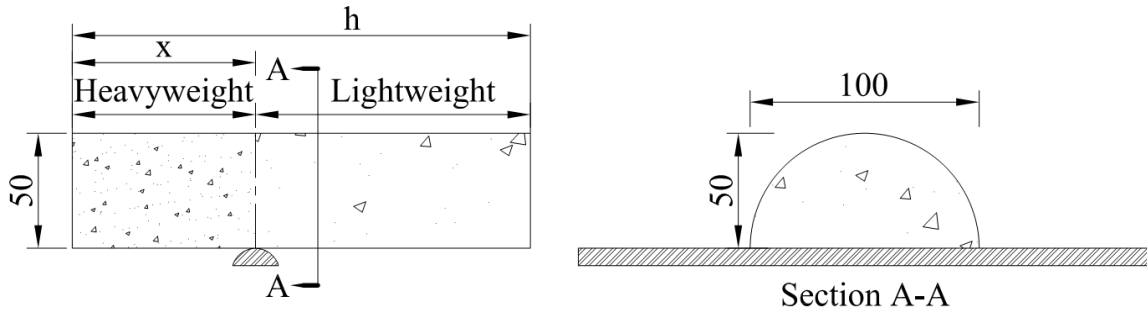


Figure 4.10 – Configuration of apparatus to find centre of mass of stratified cylinders

The stratification coefficient was found by using the following equation:

$$\frac{h/2 - x}{h/2} \times 100 = \text{stratification} [\%]$$

Where h is the total height of the cylinder ($200 \pm 4\text{mm}$) and x is the height to the centre of gravity measured from the bottom of the structural layer. The degree of stratification for the measured samples can be rated after the stratification coefficient (SC). That is:

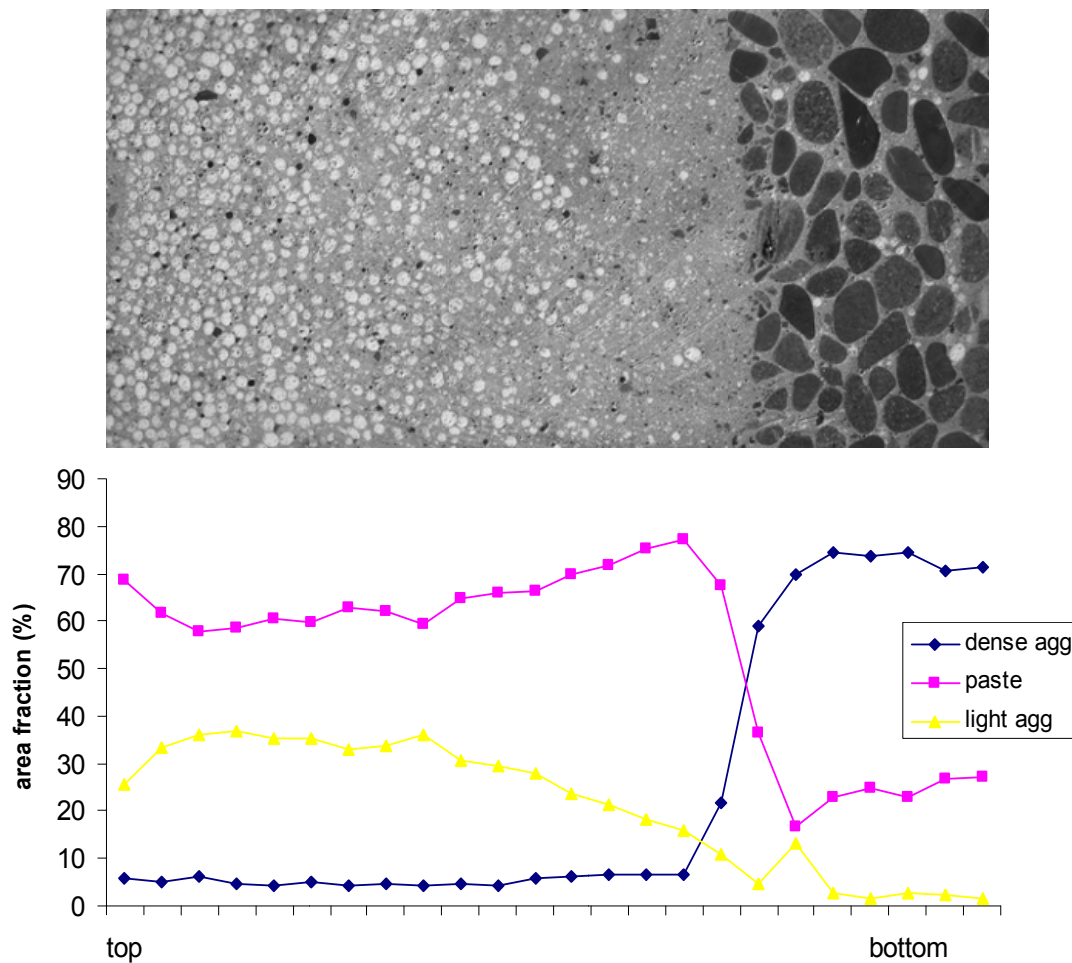
- SC that is lower than a certain percent indicates a poorly stratified sample
- SC that is higher than a certain percent indicates a well stratified sample
- SC somewhere between indicates a moderately stratified sample

The method indicated the amount of stratification well and was easy and quick to use, but the main disadvantages with using this method are:

- New mixes, containing new materials, have to be tested to find the SC percent ranks, indicating its degree of stratification
- When casting a panel or other large scale members, slices need to be cut off and measured to be able to assess the stratification coefficient

4.3.5 Assessing stratification by photo analysis

To estimate the stratification on hardened samples, a colour photograph could be taken and the amount of trapped material could be objectively assessed, as well as the level of stratification, as shown on Figure 4.11. This method is more time consuming than finding the centre of mass, but is more accurate as it indicates the amount of trapped material. This method was not used in this research.

Figure 4.11 – Photo analysis of a stratified concrete sample²¹

4.4 Hardened properties

The hardened properties that were tested were the compression strength, elastic modulus, density and flexural tensile strength. The compression strength²², density²³ and flexural tensile strength²⁴ were found by following the New Zealand Standard, NZS 3112. The elastic modulus was found by using a standard from the American Society for testing and materials; ASTM, C469-94²⁵.

4.4.1 *Compression strength*

Strength is not an intrinsic material property of concrete. Strength values are sensitive to various factors associated with the manner of their determination. The compression strength of a concrete cylinder is generally higher than that of a companion cube (same mix, same degree of

²¹ Keyte, L. & Lloyd, R. 2007

²² NZS 3112: Part 2, 1986b

²³ NZS 3112: Part 3, 1986c

²⁴ NZS 3112: Part 2, 1986b

²⁵ ASTM C 469-94, 1994

compaction, same curing history, same testing machine and same loading rate) under routine test conditions. It is therefore essential to use approved tests procedures.²⁶

The compression strength was tested on normal 200mm high and 100mm diameter cylinders and 650x150mm strips, as shown on Figure 4.12. The samples were tested by using Avery universal testing machines:

- Cylinders – Model 7112 CCG with 2500kN capacity
- Strips – Model 7104 DCJ with 1000kN capacity

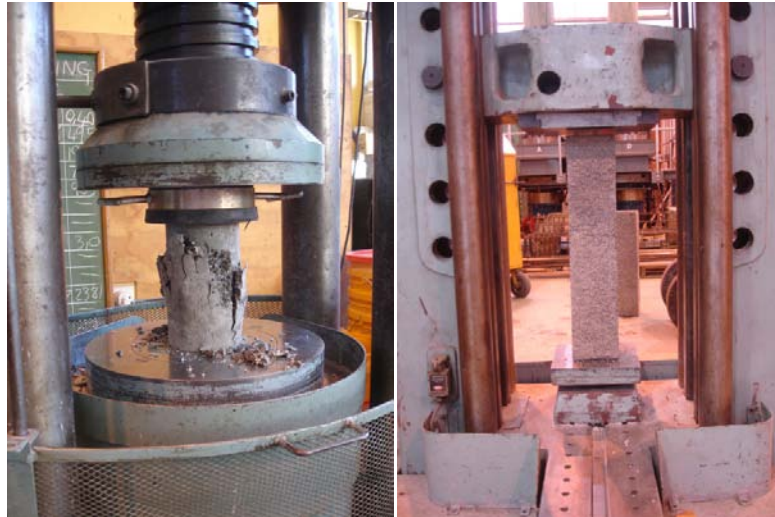


Figure 4.12 – Cylinders and strips tested for compression strength

After moisture curing the cylinders for 28days at $21\pm 2^{\circ}\text{C}$ they were tested. The ends were not allowed to deviate more than 0.5° from square, or be convex or concave by more than 0.05mm and could not contain projections above the plane surface greater than 0.05mm. Two diameters and the height were measured. The diameters were not to differ by more than 2% of their average, and the height to diameter ratio was to be between 1.90 and 2.10. After locating the cylinders centrally in the loading machine, the load was applied at a constant rate between 10 to 20MPa/min and all shock loads avoided. The load was increased until failure and the maximum load recorded.²⁷

After cutting the cast panels, 650x150mm strips were gained. From every panel, three of these strips were tested for compression strength and buckling. The curing of the strips varied depending on the curing of the panels but these were not cured according to the New Zealand Standards, NZS 3112. The ends were levelled as before and the strips placed vertically into the centre of the testing machine. As some of the ends were hard to level due to diamond saw cutting, 12-18mm plywood was placed between the ends and the machine to distribute the load evenly over the entire cross-section of the strips. Despite possibly having a small influence on the test results this was preferred over having an uneven load distribution when testing. The specimens were loaded at a constant rate between 1 to 2MPa/min and all shock loads avoided

²⁶ CCANZ, 2006

²⁷ NZS 3112: Part 2, 1986b

until the strips failed. The maximum load carried by the strips during testing was recorded and the compression strength calculated by using:

$$\sigma [MPa] = \frac{F_{max} [N]}{A [mm^2]}$$

Where σ is the axial compressive strength of the specimen, F_{max} is the maximum load and A is the cross-sectional area.

4.4.2 *Flexural tensile strength and displacement*

The flexural tensile strength and displacement was measured on 650x150mm strips cut from cast panels. The curing of the strips varied, depending on the curing of the panels so they were not cured according to NZS 3112. On Figure 4.13, the apparatus used to test the flexural tensile strength and to measure the vertical displacement under loading can be viewed. An Avery universal testing machine, model 7109 DCJ with 100kN capacity was used to gain the flexural tensile strength, and the displacement was found by placing a small metal bar over the middle of the strips and measure the displacement of both ends.



Figure 4.13 – Testing machine used to get the flexural tensile strength and displacement of the strips

In Figure 4.14, appropriate apparatus according to NZS 3112 for flexural test by third point loading method is shown. The apparatus has to ensure that the forces applied to the specimen (beam) are vertical and without any eccentricity. The NZS 3112 was followed as much as possible but with a few exceptions described below.

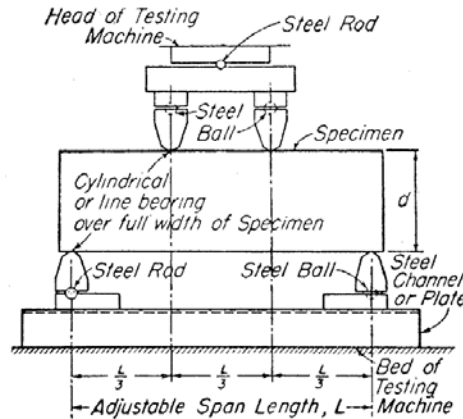


Figure 4.14 – Suitable apparatus for flexural test by third point loading method²⁸

According to NZS 3112, part b the test specimen must be tested over a span that is at least three times but not more than four times its depth. The strips tested here were 100-120mm deep with a span length of 600mm, so this requirement was not fulfilled. The strips were centred on the bearing blocks with the top surface of the panel facing the load applying blocks. The load blocks were put into contact with the specimens at the third points between the supports. Constant load was applied without any shocks, at a constant rate of 1 to 2MPa/min until the specimen failed. The maximum applied load was recorded to calculate the tensile flexural strength. The average width and depth of the strips were measured at the section of failure, as well as the distance between the line of fracture and the nearest support along the bottom centre line, to an accuracy of 1mm.

When the fracture occurred within the middle third of the span length, the flexural tensile strength was calculated to the nearest 0.2MPa by using:

$$T_f[\text{MPa}] = \frac{PL}{bd^2}$$

When the fracture occurred by more than 5% of the span length outside the middle third, the flexural tensile strength was calculated to the nearest 0.2MPa by using:

$$T_f[\text{MPa}] = \frac{3Pa}{bd^2}$$

Where T_f is the flexural tensile strength, P is the maximum load [N], L is the span length [mm], b is the average width [mm], d is the average depth [mm] and a is the distance between the line of fracture and the nearest support [mm].²⁹

To measure the displacement an instrument shown on Figure 4.15 was used. A small metal bar was placed at the top, in the middle of the specimen and the vertical displacement was measured at both ends of the bar 7 times per second. The displacement of the strip was assumed to be the average of the bar displacements. The surface where the bar was placed was levelled to minimise the likelihood of the bar tilting. Taking the average displacement of both ends, allows for minimum tilting to occur as it evens out. That is, if one end starts going down the other end goes up, evening out the displacement change.

²⁸ NZS 3112: Part 2, 1986b. p.15

²⁹ NZS 3112: Part 3, 1986c

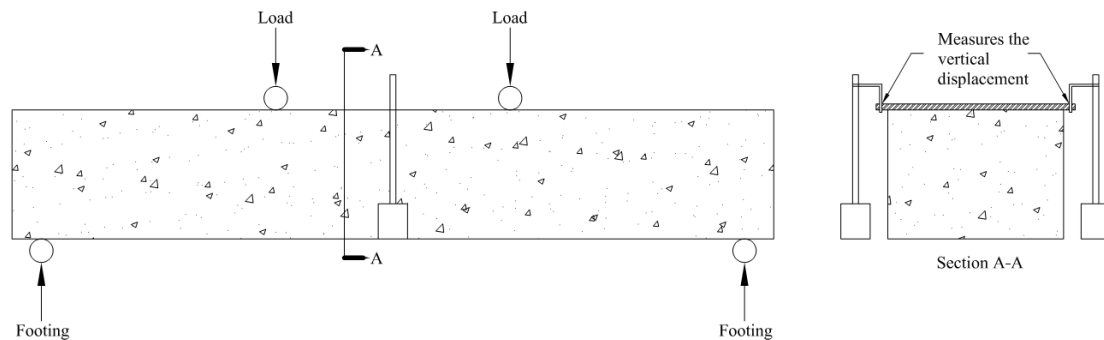


Figure 4.15 – Apparatus used to measure the displacement at the centre of beams under vertical loading

4.4.3 *Density of hardened concrete*

In the NZS 3112, the density of hardened concrete is determined from the mass of a specimen in a prescribed moisture condition and its volume when saturated. The smallest dimension of the specimen is to be not less than four times the nominal maximum aggregate size of the concrete. This size requirement is therefore easily met as all the density measurements were done on 200mm high and 100mm diameter cylinders.

The density was measured on saturated cylinders after being wet cured for 28days. The surface water was wiped off to determine the mass of the specimen in air. The specimen was also placed in a stirrup sitting in a clean water bath at room temperature and the mass difference recorded. The saturated density (ρ_s) of the specimen was found by using following equation:

$$\rho_s \left[\frac{\text{kg}}{\text{m}^3} \right] = \frac{M}{M - V} \times 1000$$

Where M is the mass of the specimen in air and V is the mass difference. The density was recorded to the nearest 10kg/m^3 .³⁰

4.4.4 *Elastic modulus*

To estimate the modulus of elasticity the ASTM C 496-94 (American Society for Testing and Materials) was used as a guideline. The method is based on a stress to strain ratio value, where the customary working stress range is 0 to 40% of the ultimate concrete strength. The values obtained will usually be less than a moduli derived under rapid load application (dynamic or seismic) and greater than when under slow application or extended load duration.

The test was performed on 200mm high and 100mm diameter cylinders that were moisture cured for 28 days. The samples were prepared with two opposite gauge lines, each parallel to the axis, and each centred about mid-height of the specimen. The effective length of the gauge lines are to be no less than three times the maximum aggregate size within the concrete and no more than two thirds of the height of the specimen. Here, the preferred length of one half of the height of the specimen or 100mm was used.

³⁰ NZS 3112: Part 3, 1986c

To apply load on the specimens, the Avery universal testing machine used to test compressive strength of cylinders was used (7112 CCG). The ends of the cylinders were prepared in the same manner as when tested for compression strength, and the same measurements done as before. The specimen is located centrally and loaded twice to approximately 40% of the ultimate load of the specimen, at a constant rate between 10 to 20MPa/min and all shock loads avoided. This is primarily done to seat the gauges. After preloading the samples, the load is set to a low value between 5 and 10kN, and the distance between the gages were measured with a Staeger strain gauge, as shown on Figure 4.21. This process is repeated with applied load of 40% of the ultimate load. To find the longitudinal strain the total longitudinal deformation is divided by the effective gauge length. The modulus of elasticity is determined by using following equation:

$$E [GPa] = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\Delta F/A}{\Delta l/a}$$

Where:

- E is the elastic modulus
- $\Delta\sigma$ is the stress difference
- $\Delta\varepsilon$ is the strain difference
- ΔF is the difference between 40% ultimate load value and the low force value
- A is the cross-sectional area
- Δl is the average change in length of the gauge line measured with low applied load and at 40% of the ultimate load
- a is the length of the gauge line or 100mm

4.5 Serviceability

To quantify the serviceability of the variable density concrete, drying shrinkage and the amount of warping or curling were measured.

4.5.1 Drying Shrinkage

Drying shrinkage was measured in accordance with the Australian Standard, AS 1012.13-1992, where concrete is wet cured and then air dried for a specific time while the change in length is measured. The drying room is kept at a $23\pm1^\circ\text{C}$ temperature with a relative humidity of $50\pm5\%$ and the air is circulated to maintain the specified conditions to all the specimens.

Shrinkage moulds are displayed on Figure 4.16 and consist of:

- A base plate with two end plates that are securely fastened by screws
- Two side plates which are fastened to the end plates by screws
- Two particularly loose end plates which act as gauge stud holders
- Two gauges with a diameter of 6mm, length of $22.5\pm0.1\text{mm}$ and flat ends perpendicular to its length

The samples measured are $75\times75\times280\pm1\text{mm}$ with the inner ends of the two studs being $250\pm0.5\text{mm}$.

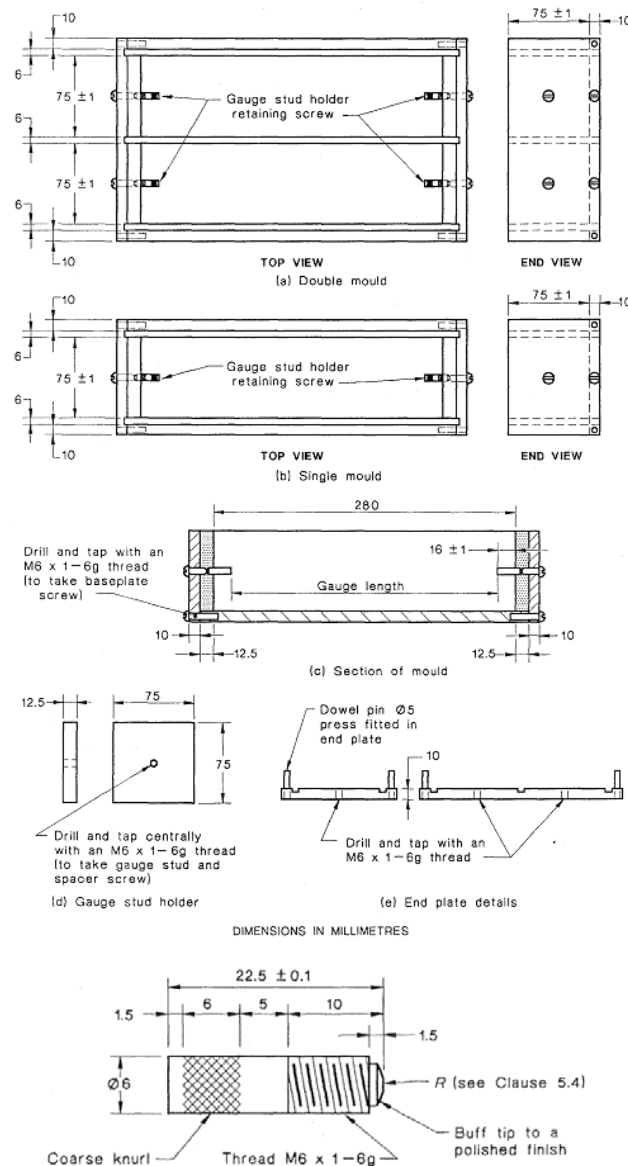


Figure 4.16 –Typical mould used to cast shrinkage prisms³¹

The comparator used for measuring the length changes had to be capable of measuring length of specimens over a range of 290 to 300mm, with a precision of 0.001mm but the comparator used here can be viewed on Figure 4.17.

³¹ AS 1012.13-1992

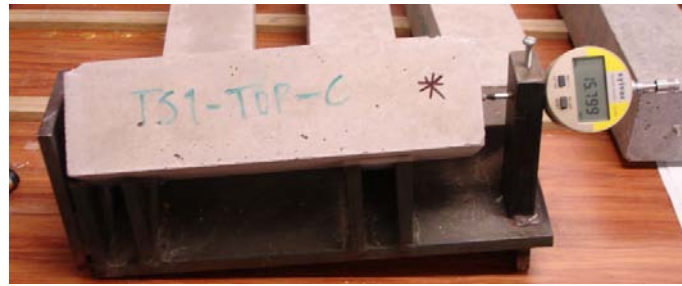


Figure 4.17 – Comparator used to measure changes in length of the shrinkage prisms

The samples were demoulded approximately 24hours after being cast and wet cured at 21°C for 7days until the initial length measurement was taken.

After taking the initial measurements, the samples are placed on racks in the drying room with a minimum clearance of 50mm on all sides except for the necessary support. The samples were measured at approximately 7, 14, 21, 28 and 56days after being placed in the drying room.

Drying shrinkage is usually expressed in microstrains, and can be calculated by:

$$\text{Shrinkage [microstrain]} = \frac{L_{in} - L}{250\text{mm}} \times 1000$$

Where L_{in} is the initial length [mm] and L is the measured length after curtain time [mm]. The original effective gauge length shall be taken as 250mm. The drying shrinkage is taken as an average of three measured samples.³²

4.5.2 *Warping or curling*

There are not many approved test methods available to test warping or curling of concrete, and especially not for concrete panels. Curling tests used for slabs, pavements and repairs in concrete were modified to measure curling in panels. One of the test methods used, is based on measuring strain, vertical displacement and horizontal displacement to find the shrinkage and thereby the curling. The Structural Preservation System (SPS) plate is another method being developed to measure warping in concrete repairs and should become recognised and more widely used soon.³³

One of the major problems in repairing concrete is the high failure rate of concrete repairs. Generally, the failure is related to cracking of repair materials often as a result of dimensional incompatibility between the repair material and the concrete substrate; that is curling. SPS plate test is a restrained drying shrinkage test method that was found to be good for general assessment of materials dimensional compatibility, or resistance to cracking. Modifications to specimen details and instrumentation are necessary to make this promising test more precise.³⁴

In the SPS plate test the deflection of the unstrained end of the beam specimen was measured as the material in the beam expanded or contracted in response to temperature and moisture changes, Figure 4.18.

³² AS 1012.13-1992

³³ McDonald, J.E.; Vaysburd, A.M. & Poston, R.W. 2000:1-12

³⁴ McDonald, J.E.; Vaysburd, A.M. & Poston, R.W. 2000:1-12

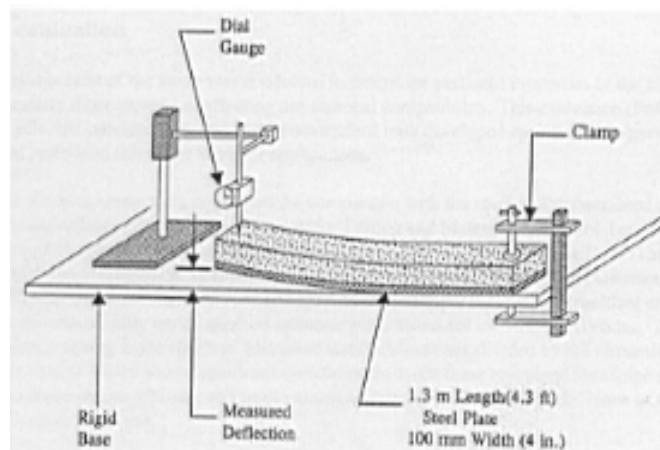


Figure 4.18 – Configuration of the Structural Preservation System (SPS) plate test³⁵

Due to lack of space and equipment, as well as having large panels, it was decided not to carry on using this test. Wanting the panels to stand vertically meant that they could not be clamped into the apparatus at all times, and by replacing the panels the amount of restraint had to be monitored. Other issues that had to be controlled were:

- The lightweight material at the top crushed when clamped. This made the amount of restraint hard to control
- The panels experienced both concave and convex movements at early age. That meant that the samples had to be held up by the apparatus to be able to measure movements in both upwards and downwards directions

Some concrete slabs were poured under different curing conditions as the temperature, moisture and creep effect on curling or warping behaviour of joint concrete pavements were to be examined. The self-weight of the slab tries to prevent curling and warping but as a side effect, internal stresses or restraint stresses are built up inside the slab. The difference in curling and warping behaviour between these curing methods were studied with respect to the deformations and the strains of the slab, Figure 4.19.³⁶

³⁵ McDonald, J.E.; Vaysburd, A.M. & Poston, R.W. 2000:4

³⁶ Jeong, J.H. & Zollongor, D.G. 2004:66-74

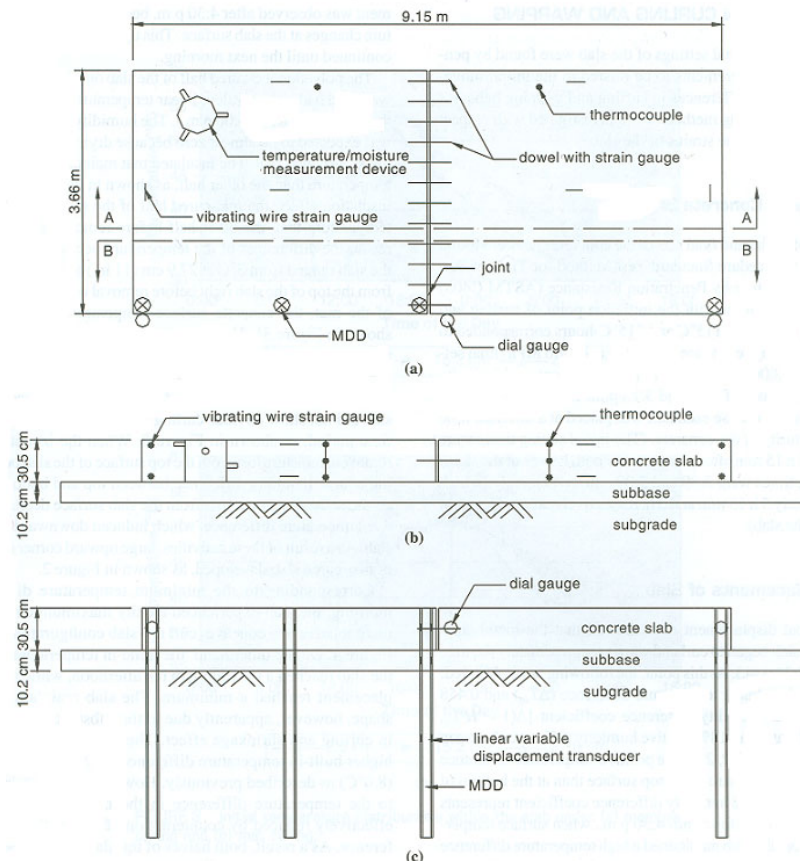


Figure 4.19 – Layout of test slab instrumentation where a) is a plan view, b) section A-A and c) section B-B³⁷



Figure 4.20 – Configuration used to measure upward movement and strain differences of stratified strips

The strains as well as the upward movement were measured on 120x120x470mm, 150x120x530mm and 150x150x530mm strips, Figure 4.20. The sides of the strips were sealed to prevent all moisture loss from the sides and they were stored standing vertically to simulate the behaviour experienced in a wall panel.

³⁷ Jeong, J.H. & Zollongor, D.G. 2004:67

Trying to simulate the SPS plate test, one end of the strips were clamped down or restrained on a straight surface table, and the amount of upward movement on the other end was measured using feeler gauges, Figure 4.20. As the method did not give satisfactory results; further development on this test method was not carried out.

On the stratified side of the strips strain gauges were placed and the strain measured using a Staeger strain gauge shown on Figure 4.21. The difference between measurements was small and no correlation was found. As well as measuring strain on the beams, some strain gauges were placed on the centre line of the outdoor exposed panels (described later in this chapter). The measurements did not give any useful information so the measurements were not continued. Measuring the strain difference was found unsuccessful to estimate the amount of warping.



Figure 4.21 – Staeger strain gauge

As known methods did not give a good indication of the amount of warping a new method had to be developed. The method found giving the best results was to place a straight edge on the bottom surface of the samples and the deflection measured by using feeler gauges as shown on Figure 4.22. This was done on strips approximately $650 \times 150 \times 110 \text{ mm}$ and $1350 \times 80 \times 120 \text{ mm}$ as well as on panels approximately $1000 \times 700 \times 110 \text{ mm}$. The samples being tested were cast using different mix designs and cured in various environments as well as having a different amount of stratification. The stratified sides were sealed to prevent any moisture loss through these areas and the samples were stored standing vertically. This test method was easily performed, as the samples simply had to be placed down from standing vertically before being measured but did not have to be restrained. In some cases the paste layer tended to scrape off as the deflection was being measured by using the feeler gauges but this was not found to be a severe problem. Using a straight edge and feeler gauges was found to give a good indication of the amount of warping experienced as the variable density panel cured.

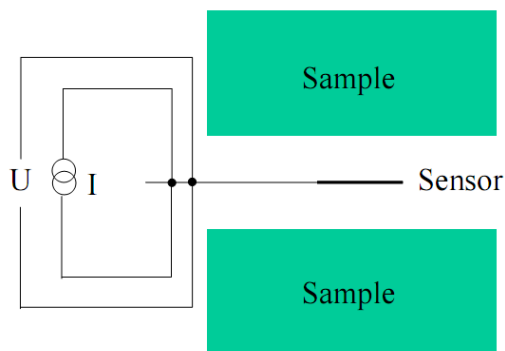


Figure 4.22 – Configuration of warping measurements performed using a straight edge and feeler gauge

4.6 Thermal properties

A non-steady state method of thermal analysis (Transient Plane Source (TPS)) was used to provide rapid measurements of the thermal performance. It is a modern technique that gives information about the thermal conductivity, thermal diffusivity and specific heat per unit volume of the material under study.

The method, Hot Disk Thermal Constants Analyser, is based on the use of a transiently heated plane sensor. The Hot Disk sensor consists of an electrically conducting pattern in the shape of a double spiral (Nickel foil) which is sandwiched between two thin sheets on an insulating material. The Hot Disk sensor is fitted between two plane surface pieces of the sample being tested. An electrical current that is high enough to increase the temperature of the sensor by several degrees is passed through the sample, and the resistance (temperature) increase is recorded as a function of time. The Hot Disk sensor is therefore a heat source and a dynamic temperature sensor.³⁸



- Sensor between sample pieces
- Source I (current intensity), Sense V (voltage/potential)
- Calculate initial R (resistance), $R_0 = V/I_0$, temperature dependent
- Calculate effect, $P_0 = R_0 \times I^2$
- Different sensor sizes, different areas

Figure 4.23 – Measurement with the Hot Disk Instrument³⁹

The thermal parameters are gained by using:

$$R = R_0(1 + \alpha\Delta T)$$

$$\Delta T = \frac{\alpha P_0}{a\lambda} \times F(\tau)$$

Where:

- R is the probe resistance
- R_0 is the initial resistance
- α is the temperature coefficient [K^{-1}]
- T is the temperature [K]
- P_0 is the sensor effect
- a is the sensor area
- λ is the thermal conductivity
- $F(\tau)$ is information about κ
- κ is the diffusivity

³⁸ Gustafsson, S. 2005

³⁹ Dinges, C

When ΔT is plotted against $F(\tau)$ the best fit gives the diffusivity and the slope gives the conductivity. The specific heat is found by using:⁴⁰

$$C_p = \lambda / \kappa$$

The thermal conductivity measures the ability of a material to conduct heat, and is defined as the ratio of heat flux to temperature gradient, whereas the specific heat is the amount of heat per unit mass required to change the temperature of a material by one degree.

Three types of samples were prepared:

- Concrete cylinders – 200mm high and 100mm in diameter were cut vertically down the middle, these cylinders were cut after one day of curing and placed in a drying environment. The thermal measurements were done at 28days after demoulding
- Concrete cylinders – 250mm high and 150mm in diameter were cut vertically down into 4 equally sized samples. Two of these were used for thermal testing and one was cut further down to find the density of each section being measured
- Concrete cylinders – 250mm high and 150mm in diameter were cut vertically down the middle and then cut into 5 equally sized half cylinders

The larger cylinders were cut down after being moisture cured for 21days and placed in a drying environment. After being dried for 7days and 35days they were tested for their thermal performance and the density of measured. The arrangement of these thermal testing can be viewed on Figure 4.24.

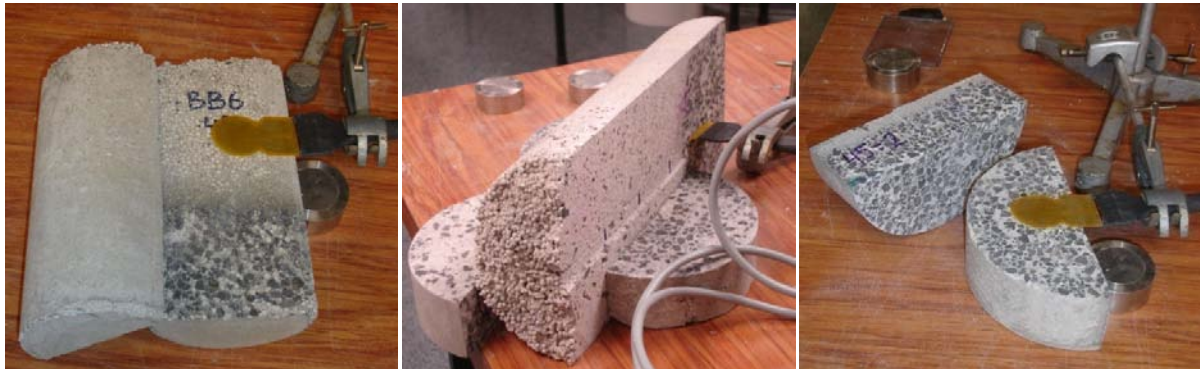


Figure 4.24 – Thermal testing of stratified concrete samples

The R-value (total thermal resistance) was calculated by using:

$$R - value = \frac{thickness}{thermal\ conductivity}$$

4.7 Durability

Two durability index tests were performed; water sorptivity and oxygen permeability. The 200mm high and 100mm diameter cylinders tested were moisture cured for 28days before they were cut down to approximately 25mm thick slices. The slices were oven dried at 50°C for at least 7days to produce uniform moisture content within the samples. The water sorptivity was

⁴⁰ Dinges, C

tested on stratified cylinders and on cylinders containing material from the top and bottom layer while the oxygen permeability was only tested on stratified cylinders.

4.7.1 *Water sorptivity*

“Absorption is the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces.”⁴¹ Sorptivity on the other hand, is defined as the rate of movement of a wetting front through a porous material under the action of capillary forces. Several general absorption tests have been developed where a concrete sample is immersed in water and the total mass absorbed used as a measure of the absorption. These tests measure the porosity of the concrete but do not quantify the rate of absorption and do not distinguish between surface and bulk effects.⁴²

Here, a modified version of Kelham’s sorptivity test was used.^{43, 44} The circular edges of the sample were sealed using tape to ensure unidirectional absorption and the samples placed on wet paper towels to expose them to a few millimetres of water as shown on Figure 4.25. When testing, the tape was folded over the top surface but should have been trimmed off so that both ends would be fully exposed as shown on Figure 4.26.

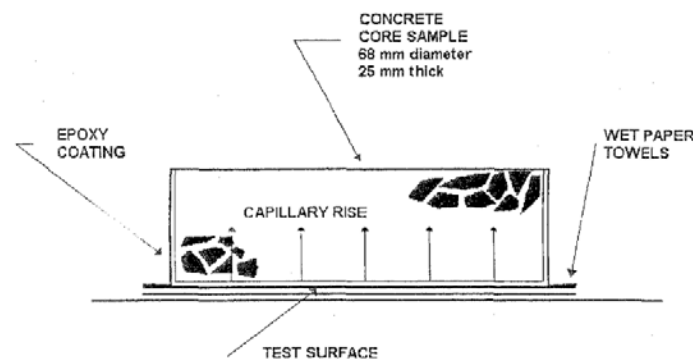


Figure 4.25 – The water sorptivity test used⁴⁵

At 0, 1, 2, 4, 8, 16, 32 and 64 *minute* time intervals, the samples were removed from the water and the mass of water absorbed measured by using an electronic balance. The samples are finally vacuum-saturated to determine the effective porosity as shown on Figure 4.26.

⁴¹ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999, p.14

⁴² Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

⁴³ Ballim, Y. 1993

⁴⁴ Kelham, S. 1988

⁴⁵ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999. p.30



Figure 4.26 – Configuration of the water sorptivity test

When the mass of water absorbed is plotted against the square root of time, a linear relationship is observed, and the slope determines the sorptivity (S), such that:

$$S = \frac{\Delta M_t}{t^{1/2}} \times \frac{d}{M_{sat} - M_0}$$

Where ΔM_t is the change of mass with respect to the dry mass [g], M_{sat} is the saturated mass of concrete [g], M_0 is the dry mass of concrete [g], d is the sample thickness [mm] and t is the period of absorption [hr].⁴⁶

4.7.2 Oxygen permeability

Permeation is the process of movement of fluids through concrete's pore structure under an externally applied pressure, whilst the pores are saturated with the particular fluid. Many tests have been developed to assess the permeability of concrete. These tests are mainly of two types:⁴⁷

- *Through flow permeability tests* try to determine the Darcy coefficient of permeability. This is done by measuring the pressure gradient (flow rate) through concrete under a sustained pressure head. These tests can take a long time and are impractical for dense concretes
- *Inflow permeability tests* measure the depth of fluid penetration after a period of applied pressure. Falling head permeameters apply an initial pressure to a concrete sample and the pressure is allowed to decay as permeation proceeds. This approach maintains a high level of accuracy since pressure may be reliably monitored with time. Inflow permeability tests are easier to perform than through flow permeability tests

Here, the falling head gas permeameters test, developed at the University of the Witwatersrand by Ballim is used, a schematic figure of the test apparatus is shown on Figure 4.27.⁴⁸

⁴⁶ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

⁴⁷ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

⁴⁸ Ballim, Y. 1991

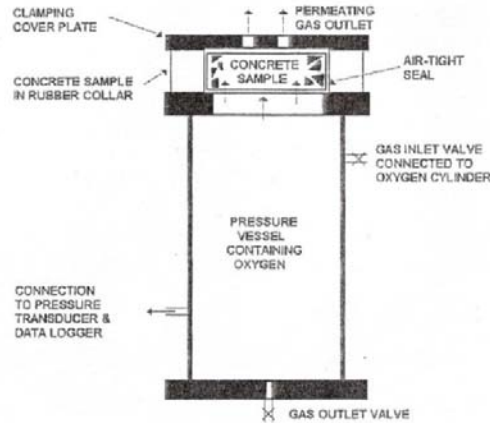


Figure 4.27 – Schematic figure of the oxygen permeability apparatus developed by Ballim⁴⁹

The permeability is determined by measuring the pressure decay with time, having the initial pressure value set as 100kPa . The pressure decay was measured by using data loggers reading the pressure every minute as shown on Figure 4.28.



Figure 4.28 – Configuration of the oxygen permeability test

The pressure decay observed was converted to a linear relationship by plotting the logarithmic ratio of pressure heads versus time. The slope of the line is the coefficient of permeability. The coefficient of permeability can also be determined by using:

$$k = \frac{\omega V g d}{R A \theta t} \times \ln \frac{P_0}{P}$$

Where k is the coefficient of permeability [m/s], ω is the molecular mass of permeating gas [kg/mol], V is the volume of the pressure cylinder [m^3], g is the acceleration due to gravity [m/s^2], d is the sample thickness [m], R is the universal gas constant [Nm/K mol], A is the cross-sectional area of specimen [m^2], θ is the absolute temperature [K], t is time [s], P_0 is the pressure at the start of the test [kPa] and P is the pressure at time t [kPa].⁵⁰

⁴⁹ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999: p.13

⁵⁰ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

The coefficient of permeability is simplified by defining the permeability index (OPI):⁵¹

$$OPI = -\log_{10}(k)$$

4.8 Sample preparation

Different samples were required depending on the test being performed.

4.8.1 *Stratified cylinders*

Normal 200mm high and 100mm diameter stratified cylinders were cast using steel moulds when optimising the mix design for further testing. The cylinders were vibrated for different amount of time and various vibration intensities applied, to determine the right time and intensity. Stratified cylinders were also used for durability and thermal testing.

4.8.2 *Large Cylinders*

In an attempt to get better thermal test results for the variable density panel, 250mm high and 150mm diameter cylinders were cast in 300mm high steel moulds. These cylinders were vibrated for 30 and 45seconds to get the different thermal properties depending on the amount of stratification. After 21days of moisture curing, these cylinders were cut down in various ways, as explained earlier.



Figure 4.29 – Mould for a 150x300mm cylinder and a comparison of a large and normal cylinder

4.8.3 *High cylinders*

Cylinders that were 500mm high and 100mm in diameter were cast to gain:

- 200mm high cylinders containing concrete from the structural bottom layer
- 200mm high cylinders containing concrete from the lightweight top layer

The moulds were made from plastic tubes that were cut down the centre. The two pieces were carefully put back together and fitted into a steel frame before pouring concrete into them. Vibrating the concrete produced stratified cylinders containing top and bottom material. The vibration time varied from 30-60seconds depending on the mix design.

⁵¹ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

These cylinders were used to test hardened performance of the concrete; that is compression strength, elastic modulus and density, as well as being used to measure the water sorptivity. This method was not found to improve the method of using a bucket as described below. Properly stratified cylinders could not be guaranteed and in some cases the top part of the structural cylinders consisted of paste and lightweight material.

Another issue concerning these high cylinders was that the moulds were made out of plastic and by cutting them down the middle weakened the moulds even further. The cylinders cast were oval, having one diameter around 96mm and the perpendicular one around 107mm . This is not ideal when testing concrete cylinders.



Figure 4.30 – High cylinder mould

4.8.4 **Bucket to get standard cylinders and prisms**

To gain samples containing material from the structural layer and separate samples containing material from the insulating top layer, a 25L bucket was used. The concrete was poured into the bucket and then stratified. The top material was poured into one mould and the bottom material into another. This method was both used to get cylinders to test hardened properties and water sorptivity of the layers, as well as to gain shrinkage prisms.



Figure 4.31 – 25L bucket containing stratified concrete

If better consistency between trials was required, a bucket which one could put metal plates inside could be used. That is, after stratifying the concrete the metal plates would be slipped in to separate the layers. This was not considered necessary since good samples were gained by the simple use of a 25L bucket.

4.8.5 **Strips**

Strips that were $120 \times 120 \times 470\text{mm}$, $150 \times 120 \times 530\text{mm}$, $150 \times 150 \times 530\text{mm}$ and $1350 \times 80 \times 120\text{mm}$ were cast when estimating the warping or curling of the stratified concrete. All these strips contained $\varnothing 4\text{mm}$ steel bar in the structural layer. The steel was placed in the centre line with 20mm cover.

4.8.6 **Panels**

Half scale panels were cast, that is 1000x700x120mm as shown on Figure 4.32, but in some cases the thickness was only between 105mm and 120mm. This was due to wrong densities of the aggregate materials being used and having a 100L mixer capacity. The lightweight material was fluffy and tended to get thrown out of the mixer if over filled. The panels all contained Ø4x75x75mm steel mesh in the bottom, structural layer with 20mm cover.



Figure 4.32 – Panel being cast on the vibrating table

The panels contained different materials and were cured under various environmental conditions. After measuring the amount of warping on most of the panels they were cut down into 6 650x150mm strips that were tested for warping, axial compression strength and flexural tensile strength.



Figure 4.33 – Panels left standing outside for just under 5 months for durability testing

4.9 References

- Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999. “*Guide to the use of durability indexes for achieving durability in concrete structures.*” Departments of Civil Engineering University of Cape Town, Cape Town, South Africa.
- American Society for Testing and Materials. ASTM C 469-94, “Test Method for Static Modulus of Elasticity and Poisson’s Ratio for Concrete in Compression.” ASTM International, West Conshohocken, Pa., 1994.
- Australian Standards. 1992. *AS 1012.13-1992, Methods of testing concrete. Method 13: Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory.* Standards Australia.
- Ballim, Y. 1991. “A low cost falling head permeameters for measuring concrete gas permeability.” *Concrete Beton* 61:13-18.
- Ballim, Y. 1993. “Curing and the durability of OPC, fly ash and blast-furnace slag concretes.” *Materials and Structures* 26(158):238-244.
- Bui, V.K.; Montgomery, D.; Hinczak, I. & Turner, K. 2002. “Rapid testing method for segregation resistance of self-compacting concrete.” *Cement and Concrete Research* 32: 1489-1496.
- Cement & Concrete Association of New Zealand (CCANZ). 2006. *Concrete Testing, CCANZ One Day Courses.* CCANZ, Cement & Concrete Association of New Zealand.
- ConTec Ltd. 2003. “*The ConTec –BML Viscometer, Viscometer 4&5, Operating Manual.*” ConTec Ltd. Laugarvegi 7, Reykjavík, Iceland.
- ConTec. 2006, 21st November. BML-Viscometer. Web site: <http://www.itn.is/contec/>
- Dinges, Carl. “*The Hot Disk Bridge system Measurements and Equipment.*” Hot Disk AB, Sweden.
- El-Chabib, Hassan and Nehdi, Moncef. 2006. “Effect of Mixture Design Parameters on Segregation of Self-Consolidating Concrete.” *ACI Materials Journal* 103: 374-383.
- Gustafsson, S. 2005. “*Hotdisk thermal constant analyzer – Instruction manual version 5.0*”, Gothenburg.
- Jeong, Jin-Hoon and Zollonger, Dan G. 2004. *Early-Age Curling and Warping Behaviour; Insights from a Fully Instrumented Test-Slab System.* *Transportation Research* 1096: 66-74.
- Kelham, S. 1988. “A water absorption test for concrete.” *Magazine of Concrete Research* 40(143):106-110.
- Keyte, Louise and Lloyd, Redmond. 2007. “*Stratified Panel IPC report*” September 2007, University of Canterbury, Christchurch, New Zealand.
- Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007. “Stratified Precast Concrete Panels for Buildings.” *Concrete Plant International*, July 2007.
- McDonald, James E.; Vaysburd, Alexander M. & Poston, Randall W. 2000. *Performance Criteria for Dimensionally Compatible Repair Materials.* High-Performance Materials and Systems Research Program, Information Bulletin.
- New Zealand Standards. 1986a. *NZS 3112: Part 1:1986, Specification for Methods of Test for Concrete, Part 1, Tests relating to fresh concrete.* NZS, New Zealand Standard.

- New Zealand Standards. 1986b. *NZS 3112: Part 2:1986, Specification for Methods of Test for Concrete, Part 2, Tests Relating to the Determination of Strength of Concrete*. NZS, New Zealand Standard.
- New Zealand Standards. 1986c. *NZS 3112: Part 3:1986, Specification for Methods of Test for Concrete, Part 3, Tests on hardened concrete other than for strength*. NZS, New Zealand Standard.
- Park, Y.S. 2006, Research proposal, Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Poraver. 2007, 20th of February. Web site: <http://www.poraver.com/>

5 Fresh Properties

Workability is defined as the property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished.¹ Rheology is the science of the deformation and flow of matter and involves stress, strain, rate of strain and time.² Important rheological properties are defined as follows³:

- Yield shear stress is caused by inter-particle forces within concrete such that the material appears stiff until these links are broken by shear
- Plastic viscosity is the resistance to flow once the yield stress has been exceeded
- Shear rate is a measure of the rate of strain within the material during testing and should replicate likely levels during placing and compaction

Vibration removes the yield stress of fresh concrete, which then flows under its own weight and allows entrapped air to be released.⁴

Segregation is separation of constituents of a heterogeneous mixture so that their distribution is no longer uniform. Concrete consists of materials having various densities so gravity works against homogeneity.⁵ In fresh concrete the start of settlement of coarse aggregate particles depends on the yield stress of the mortar, the density difference between the aggregate particles and the mortar as well as the size of the coarse aggregate. Once movement occurs, the velocity of the settlement is affected by the plastic viscosity of the mortar rather than the yield shear stress.⁶

Having certain fresh properties allows the lightweight and normal/heavyweight aggregates to segregate in opposite directions. The physical phenomenon is however the same:⁷

- Lightweight aggregates often have lower particle densities than the mortar matrix in the concrete, causing upward movement of the coarse aggregates
- Normal/heavyweight aggregates have higher particle densities than the mortar matrix in the concrete, causing downward movement of the coarse aggregate as they sink

By using simple physics it was possible to stratify fresh concrete made with lightweight and heavyweight aggregates. Stratification of concrete is defined as controlled segregation under vibration.

To ensure that the variable density concrete would stratify, the concrete mix had to have defined fresh properties; that is, slump flow and rheological properties within a limited range. The amount of stratification had to be assessed in the fresh and hardened state to ensure satisfactory stratification. Initially, three broad rheological regions were defined as:⁸

¹ Neville, A.M. 1995:184-9

² Mackechnie, J.R. 2006

³ Banfill, PFG. 2003

⁴ Mackechnie, J.R. 2006

⁵ Roussel, N. 2006

⁶ Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

⁷ Chia, K.S; Kho, C.C. & Zhang, M.H. 2005

⁸ Mackechnie, J.R.; Park, Y.S.; Saevarsdottir, T & Bellamy, L. 2007

- concrete having moderate to low flow characteristics and moderate to high viscosity making the material too stiff and sticky to allow stratification
- concrete having good flow and moderate viscosity that allows stratification to occur under moderate levels of vibration
- concrete with good flow and low viscosity that is not stiff and sticky enough and segregates in the mixer or during handling

Three different mix designs were examined and developed using Portland cement as a binder:

- PUM – containing pumice and perlite as lightweight materials and greywacke chips (greywacke sandstone) as normalweight material
- GB – containing 2-4mm expanded glass beads and perlite as lightweight materials and slag as heavyweight material
- BB – containing 2-4mm and 0.5-1mm expanded glass beads as lightweight material and slag as heavyweight material

5.1 Fresh properties

Fresh properties of concrete are dependent on the material type used and their composition. The fresh properties were recorded when developing different concrete mixes as well as the calculated stratification coefficient, described later in this chapter, are listed in Table 5.1 and Table 5.2.

Table 5.1 – Fresh properties of the PUM mixes

Mix	w/b ratio	Slump flow [mm]	τ_0 [Pa]	μ [Pas]	Separation [%]	Stratification coefficient [%]	Stratification rating
PUM1	0.5	640	0	20.1	15	7.3	Poor
PUM10	0.55	495	31	19.4	12	9.7	Poor
PUM11	0.55	620	846	18.3	2	7.5	Poor
PUM2	0.7	430	73	16.6	12	7.6	Poor
PUM3	0.67	700	238	7	2	11.3	Moderate
PUM4	0.6	510	40	44	8	11.1	Moderate
PUM8	0.53	500	34	13	13	10.5	Moderate
PUM7	0.47	660	691	42	1	14.9	Mod/ Good
PUM6	0.6	640	11	23.4	20	12.8	Mod/ Good
PUM9	0.56	500	43	17.4	12	13.1	Mod/ Good
PUM5	0.54	605	3	22.3	13	16	Good

Table 5.2 - Fresh properties of the GB and BB mixes

Mix	w/b ratio	Slump flow [mm]	τ_0 [Pa]	μ [Pas]	Separation [%]	Stratification coefficient [%]	Stratification rating
GB7	0.6	485	44	35.2	14	21.5	Moderate
GB1	0.67	450	57	13.3	11	16.1	Moderate
GB2	0.67	470	40	13.9	14	20.2	Moderate
GB3	0.67	420	55	17.8	13	21.6	Moderate
GB4	0.7	440	38	14	16	21.3	Mod / Good
GB5	0.69	425	58	15.1	11	23.1	Mod / Good
GB6	0.6	600	15	13.2	8	24.8	Good
GB8	0.6	595	27	8.8	-19	25.0	Good
GB9	0.6	595	0	34.6	29	23.9	Good
BB4	0.64	455	26	8.6	7	24.3	Good
BB5	0.62	440	33	7.4	-3	28.3	Good
BB6	0.62	480	28	8.8	5	26.9	Good

5.1.1 Slump flow

One of the easiest control tests to do on site is to measure the slump flow. It was therefore hoped that the slump flow would give an indication of the stratification potential of the variable density concrete. That is, concrete within a certain range, depending on the binder and aggregate materials used, would stratify. The slump flow could not be too low, providing too sticky mixes that were hard to stratify, and not too high, risking the mix to segregate within the mixer or when being handled.

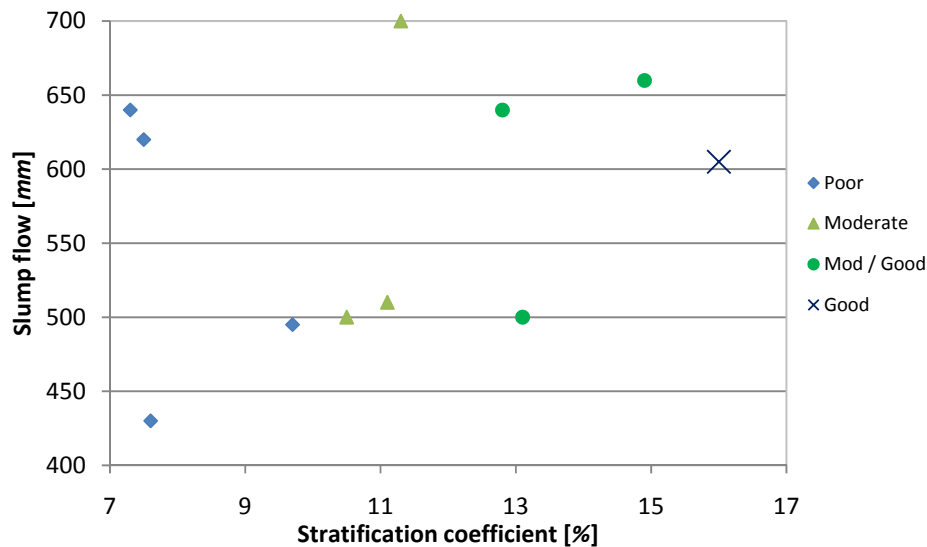


Figure 5.1 – Slump flow plotted against the stratification coefficient for the PUM mixes

Initially it was estimated that the slump flow of the PUM mixes should be between 500-650mm to allow the mix to stratify without having it segregating within the mixer. As Figure 5.1 shows a slump flow of 500mm gave poor, moderate and moderate/good stratified cylinders and a slump flow of 650mm gave both poor and moderate/good stratified cylinders. The slump flow did therefore not give any indication of the degree of stratification going to be gained. Increasing the

slump to above 650mm caused the mix to start segregating within the mixer. If the slump flow was considerably lower than 500mm the mix was too sticky, having too high yield shear stress causing the mix not to segregate.

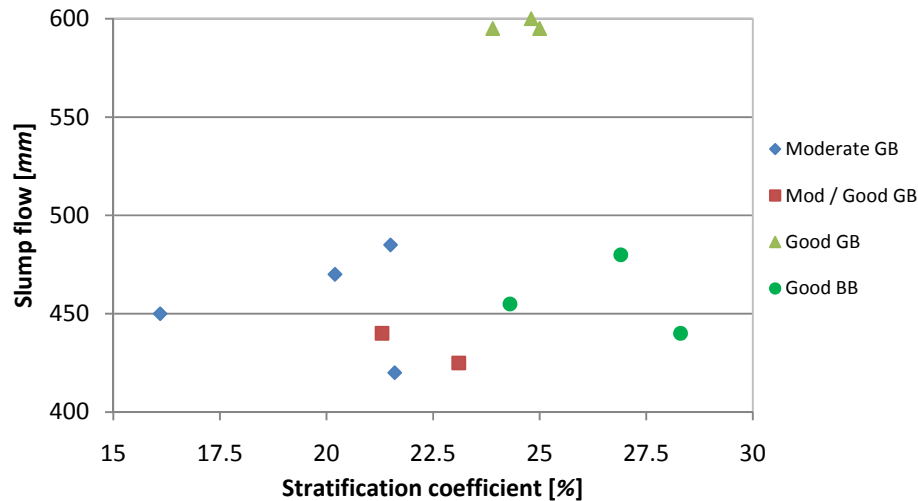


Figure 5.2 - Slump flow plotted against the stratification coefficient for mixes GB and BB

The slump flow for the GB and BB mixes was found to be smaller than for self compacting concretes, with a small material cone in the middle of the slump as shown on Figure 5.3. Initially it was estimated that the slump flow should be between 400-500mm, allowing the mix to stratify without segregating in the mixer. As displayed on Figure 5.2, the well stratified mixes generally had a slump flow above 450mm. But, that did not guarantee a good stratification, as there are several mixes only gaining moderate stratification despite having a slump flow above 450mm. As the mixes reached a slump flow of around 600mm, they started segregating while being handled. This was not observed when casting small sample cylinders but when casting panels the segregation was obvious leaving the panels with an uneven material distribution as discussed later in this chapter (Figure 5.16, Figure 5.17 and Figure 5.18). Having a slump flow below 400mm gave sticky mixes with a high yield shear stress, resulting in a poor stratification under moderate levels of vibration.



Figure 5.3 – Slump flow of a BB mix

The variable density concrete has to have a slump flow within a defined range to have the potential of stratifying, but stratification is not guaranteed. Different ranges were found for mixes containing pumice and expanded glass beads. Having too low slump flow produced sticky mixes that were hard to stratify, and as the slump flow got too high the risk of segregation within the mixer or while being handled became significant.

5.1.2 Rheology

The rheology of the fresh concrete was examined, in an attempt to define the precise rheological range for stratification of concrete. The yield shear stress and the plastic viscosity could not be too high resulting in a mix that would be too stiff and sticky to stratify.

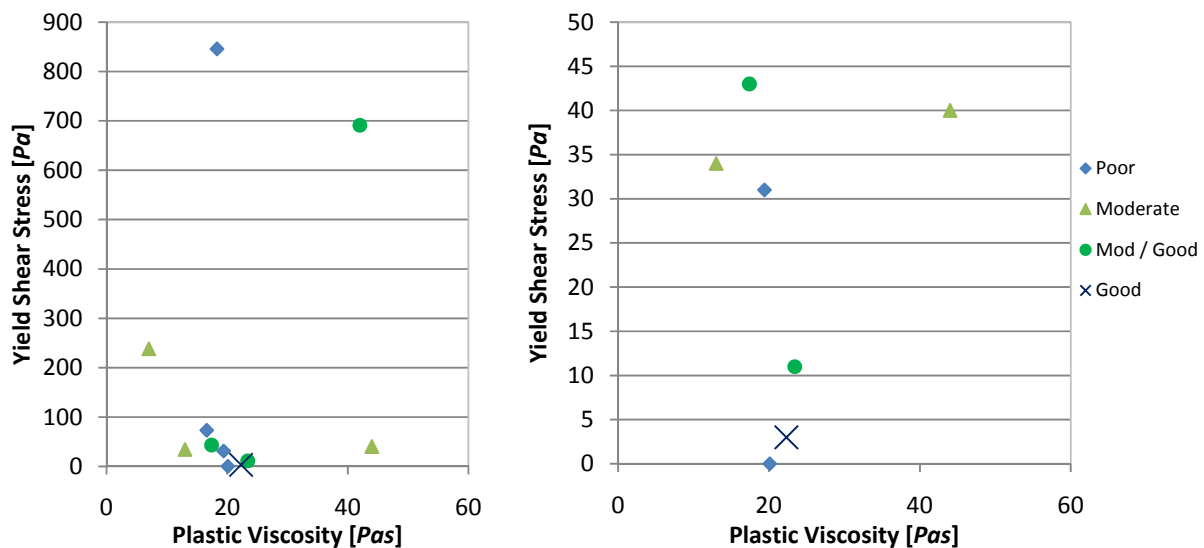


Figure 5.4 – Yield shear stress and plastic viscosity of PUM mixes; 2nd figure is a magnification of the 1st

After some initial trials it was assumed that mixes having a yield shear stress above 100Pa would be too stiff to stratify and mixes having yield shear stress below 40Pa and plastic viscosity below 30Pas would stratify easily. On Figure 5.4 it can be noticed that:

- A mix with yield shear stress above 600Pa gained moderate/good stratification just as well as mix with yield shear stress below 15Pa and plastic viscosity below 25Pas
- There are two mixes with yield shear stress below 5Pa and plastic viscosity around 20Pas gaining poor and good stratification. The poorest stratification and the best stratification are therefore gained within the same range of rheological properties
- Three out of four mixes gaining good or moderate/good stratification have a plastic viscosity between 17-24Pas and yield shear stress below 45Pa, but in that same interval there are 2 mixes gaining poor stratification

Despite having a yield shear stress below 40Pa and a plastic viscosity between 30Pas good stratification cannot be guaranteed. There are several reasons for the poor relationship found between the rheological properties and the degree of stratification but the most likely ones are:

- Inconsistency in the material properties of the pumice and the perlite
- Shapeless nature of the pumice locking it within the structural layer

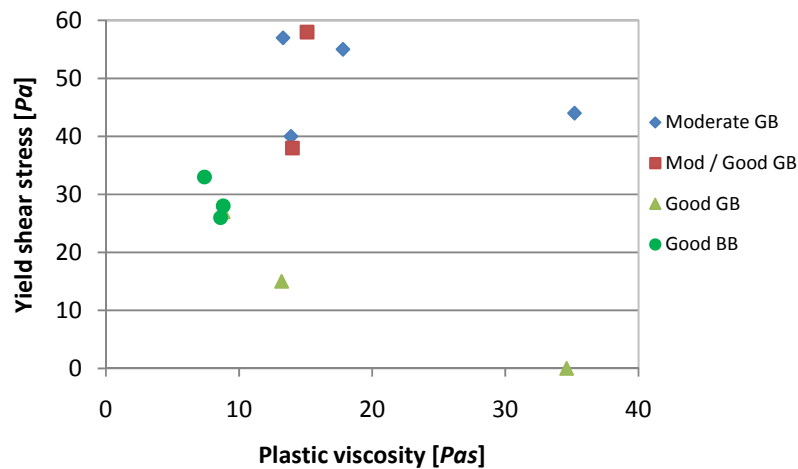


Figure 5.5 - The yield shear stress plotted against the plastic viscosity for the GB and BB mixes

From Figure 5.5, it can be assumed that for mixes GB and BB a yield shear stress below 35 Pa and a plastic viscosity below 20 Pa gives good stratification. One mix providing well stratified samples was however outside of that range, but it had a plastic viscosity of 35 Pa and a yield shear stress of 0 Pa . A clear relationship is therefore between the rheological properties and the degree of stratification for the GB and BB mixes. When examining the relationship further a linear relationship was found as viewed on Figure 5.6. On the figure, two lines were drawn where:

- All the well stratified samples are counted
- One point is neglected where the yield shear stress was 0 Pa

If excluding that one point a good linear relationship is gained, as the R^2 -value is 0.956. This linear relationship indicates that:

- The lower the plastic viscosity the higher the yield shear stress can be still allowing the mix to stratify
- The lower the yield shear stress the higher the plastic viscosity can be still allowing the mix to stratify

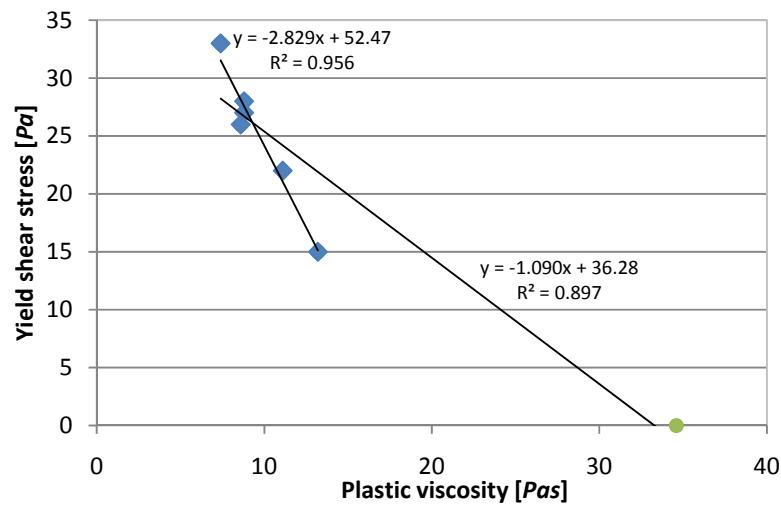


Figure 5.6 – Linear relationship between yield shear stress & plastic viscosity; well stratified GB & BB mixes

No relationship was found between the separation point found by the BML viscometer and the stratification of the samples. This was the case for all the mixes; PUM, GB and BB.

When trying to estimate the potential for stratification, the rheological properties were found more useful than slump flow. An obvious relationship between the rheological properties and the amount of stratification for the PUM mixes was not found, but when examining the GB and BB mixes, a linear relationship was found between the yield shear stress and plastic viscosity required to gain well stratified samples.

5.1.3 Variability of mixes

The fresh properties were tested and recorded for all batches cast, making it possible to check the variability of the mixes and if the batching size had any influence on the mix properties. Due to inconsistency already described in the pumice mixes, these mixes are not included here. Two GB mix designs were poured repeatedly and one BB as listed in Table 5.3.

Table 5.3 – Mix designs that were batched repeatedly

GB1		GB2		BB	
Material	1m ³	Material	1m ³	Material	1m ³
Cement	415kg	Cement	450kg	Cement	450kg
Water	275L	Water	270L	Water	280L
Fine Slag	100kg	Fine Slag	120kg	Fine Slag	120kg
Coarse Slag	400kg	Coarse Slag	310kg	Coarse Slag	410kg
Perlite	65kg	Perlite	58kg	0.5-1mm Expanded glass beads	50kg
2-4mm Expanded glass beads	50kg	2-4mm Expanded glass beads	80kg	2-4mm Expanded glass beads	94kg
		Superplasticizer	1.5L		

The fresh properties as well as the final water to binder ratio for these mixes are listed in Table 5.4 but the amount of water used was slightly adjusted when batching.

Table 5.4 – Fresh properties of three mix design GB1, GB2 and BB batch repeatedly

MIX		Batch size [L]	w/b ratio	Slump flow [mm]	τ_0 [Pa]	μ [Pas]	Separation [%]
GB1	1	20	0.69	480	22	11.1	18
	2	100	0.67	530	32	5.8	3
	3	20	0.66	-	56	22.4	11
	4	50	0.68	490	48	10.4	13
	5	50	0.70	505	53	10.7	13
GB2	1	20	0.60	595	0	34.6	29
	2	50	0.60	590	0	30.1	26
	3	110	0.63	580	2	27.5	13
	4	110	0.61	595	56	10.1	-36
	5	110	0.57	600	76	2.4	-37
BB	1	30	0.62	480	28	8.8	5
	2	25	0.62	470	26	8.9	11
	3	100	0.62	480	81	0	-28
	4	100	0.62	470	49	2.4	-16
	5	40	0.62	465	51	1.9	-27
	6	40	0.59	475	27	8.5	6
	7	30	0.61	475	32	7.1	5
	8	20	0.59	465	29	13.1	16
	9	25	0.60	475	26	6	-2

From Table 5.4 it can be noticed that the slump flows of the mixes GB2 and BB had good consistency, as the slump flow varied between:

- 480-530mm for mixes GB1
- 580-600mm for mixes GB2
- 465-480mm for mixes BB

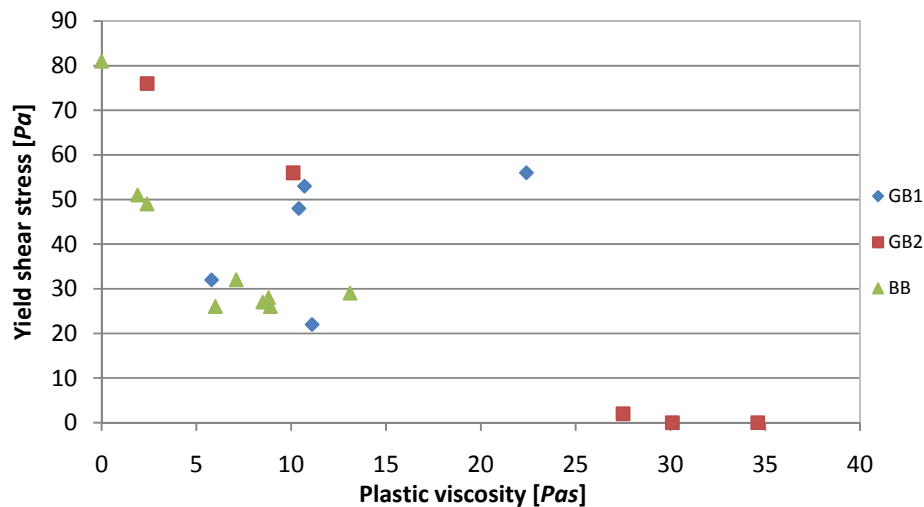


Figure 5.7 – Yield shear stress and plastic viscosity of different batches compared

In Figure 5.7 the yield shear stress and plastic viscosity are plotted for all the batches. From Figure 5.7 and Table 5.4 it can be noticed that:

- Mix BB has:
 - Yield shear stress between 26 and 32Pa and between 49 and 81Pa
 - Plastic viscosity between 6 and 13.1Pas and between 0 and 2.4Pas
- Mix GB2 has:
 - Yield shear stress between 0 and 2Pa and between 56 and 76Pa
 - Plastic viscosity between 27.5 and 34.6Pas and between 2.4 and 10.1Pas
- Mix GB1 has:
 - Yield shear stress between 22 and 56Pa
 - Plastic viscosity between 5.8 and 22.4Pas

From Figure 5.7, it can be stated that the variability of BB mixes is good, as the rheological properties tend to be of a similar magnitude. Two of the three batches that are out of range are 100L mixes that were cast when the mixer was not working properly making it hard to secure a representative sample being measured.

The rheological properties of mixes GB1 and GB2 are harder to predict. The data collected are scattered over a larger area and the results do not seem to build up around a specific point like with the BB mixes. The inconsistency within these mixes is likely to be related to the inconsistency in the material properties of the perlite. In the GB1 mixes the slag was not air dried and the moisture content of the slag was not allowed for.

5.2 Stratification

One of the major technical concerns about the variable density panels was to control the segregation (Figure 5.8); that is to allow the concrete mix to stratify during moderate levels of vibration, but remain fairly homogenous during mixing and handling. To achieve this there were several things that needed consideration, such as:

- The amount of energy varied by:

- The vibration frequency
- The vibration time
- The amplitude
- How to evaluate the degree of stratification:
 - Fresh state – penetration depth of stratified cylinders
 - Hardened state – centre of mass of stratified cylinders

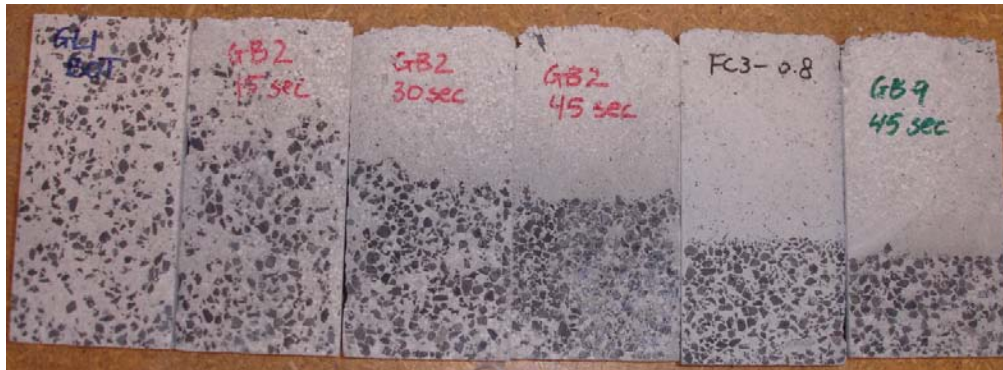


Figure 5.8 - Varying degree of increasing stratification from left to right

5.2.1 Vibration

The degree of stratification was found to be dependent on the intensity and time of the vibration. Excessive vibration affects the quality of the interface between the structural and insulating layer as well as the surface finish. Over vibrated concrete also starts losing paste from the aggregates. Limited vibration on the other hand causes poor stratification. To ensure a good quality panel which is properly stratified and without incipient delaminations, controlled vibration is essential. After some trial work using different vibration times and frequencies, mixes made using Portland cement were vibrated for 30seconds with 3000rpm (revolutions per minute) or 50Hz vibration frequency as standard.

5.2.1.1 Different vibration frequency

Stratification of concrete is dependent on the vibration intensity. Trying to optimise the vibration intensity, a comparison was made of cylinders which were cast using vibration intensities of 2500, 3000 and 3500rpm.

Figure 5.9 shows that the concrete had less stratification when 2500rpm vibration intensity was applied. This indicates that when applying 2500rpm vibration intensity, the force is insufficient to stratify the concrete properly. Vibrating the samples for a longer period of time increased the amount of stratification but was still lower than for samples vibrated using 3000rpm vibration intensity.

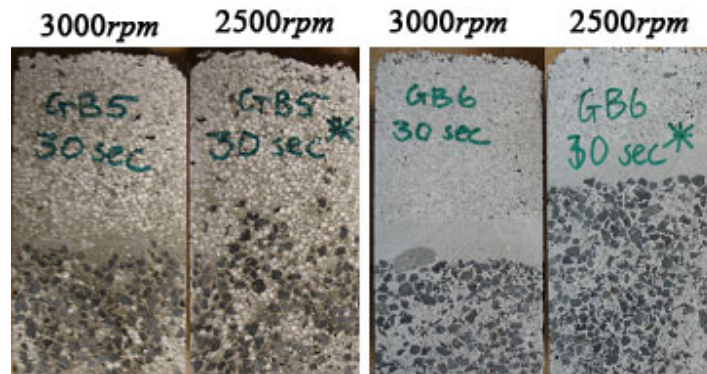


Figure 5.9 – Cylinders vibrated with 3000rpm and 2500rpm vibration intensity

Increasing the vibration intensity to 3500rpm did not seem to change the degree of stratification as displayed on Figure 5.10. When using 3500rpm vibration intensity the lightweight top layer of the samples was more likely to lose paste, and the lightweight material compacted faster trapping a few heavyweight particles within the lightweight layer.

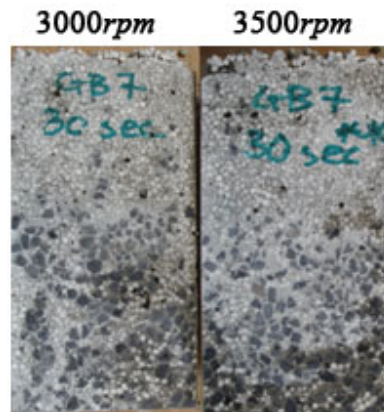


Figure 5.10 - Cylinders vibrated with 3000rpm and 3500rpm vibration intensity

It was decided to use 3000rpm vibration intensity, which is slightly higher than normally used to vibrate conventional concrete.

5.2.1.2 Different vibration times

Stratification of concrete is dependent on the vibration time. To optimise the vibration time, the samples were vibrated between 15-90seconds, depending on the mix being cast, as can be viewed in Figure 5.11, Figure 5.12 and Figure 5.13. To estimate how homogenous the mix is after handling, some cylinders were cast without any vibration.



Figure 5.11 – PUM cylinders vibrated for 15, 30, 45, 60 and 90seconds

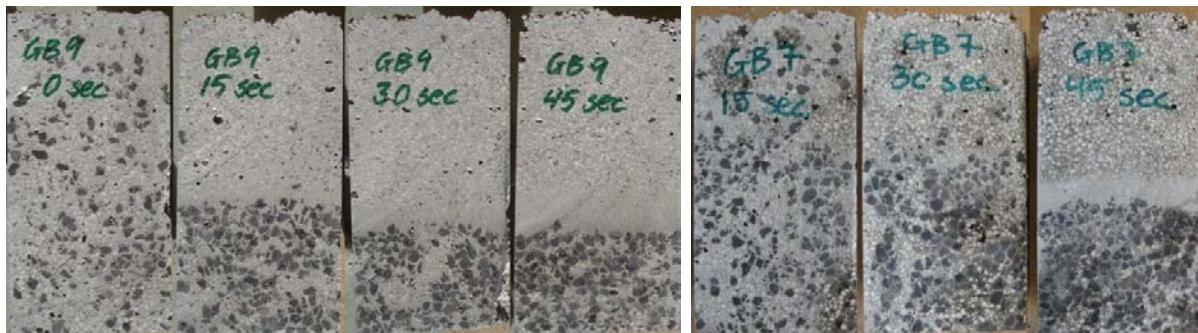


Figure 5.12 – GB cylinders vibrated for 0, 15, 30 and 45seconds



Figure 5.13 – BB cylinders vibrated for 0, 15, 30 and 45seconds

By increasing the vibration time, more stratification is gained as the pictures above display. A vibration time too short produced poorly stratified cylinders and a vibration time too long produced over stratified cylinders. The PUM mixes needed more vibration time than the GB and BB mixes. The optimum vibration times were found to be:

- 45-60seconds for the PUM mixes (Figure 5.11)
- 30-45seconds for the GB and BB mixes (Figure 5.12 and Figure 5.13)

5.2.2 Degree of stratification

Methods had to be developed to estimate the degree of stratification in the fresh and hardened state. In the fresh state, the penetration depth method was used, and on hardened samples the centre of mass was found as an estimate of the degree of stratification.

5.2.2.1 Penetration depth method on fresh concrete

To estimate the segregation of the lighter and heavier materials in a sample of fresh concrete, a penetration depth method was used. A steel plunger was dropped into the sample to measure the penetration resistance of the fresh concrete. The idea was that well stratified concrete could be subjectively confirmed when the plunger would drop freely through the insulating layer and stop at the top of the structural layer.

For well stratified standard 100Ø cylinders cast from a GB or BB mix, it was common to get a penetration depth of:

- 100-150mm after 15seconds vibration
- 0mm after 30 and 45seconds

When the samples were well stratified, the lightweight material was too compact for the plunger to drop into the sample. This method is therefore not suitable for stratified concrete but its main advantages would have been how quick and easy it is to perform when casting the variable density concrete.

The penetration depth method needs to be modified or a new method needs to be developed to estimate the degree of stratification. Only limited testing of the penetration depth method was performed as only one size of plunger was used. The method might work if a heavier plunger, a plunger with smaller diameter or a plunger with a pointed end were used. Several small plungers that would drop freely through a steel plate placed on the concrete could be developed as a new idea. An average of the penetration depth of these could then give an estimation of the stratification. These ideas were not used or investigated any further in this research.

5.2.2.2 Center of mass of stratified hardened cylinders

The degree of stratification of hardened samples had to be measured as well as estimated by viewing the samples. Here, the degree of stratification or the stratification coefficient was calculated by finding the centre of gravity of stratified samples.

PUM mixes had lower stratification coefficient to be well stratified than the GB and BB ones. This was not surprising as the density difference between the pumice and greywacke chips is less than between the expanded glass beads and slag. The stratification coefficient is therefore highly dependent on the materials being used.

Table 5.5 - Stratification of PUM cylinders

Mix	Relative density	Light-weight [%]	Heavy-weight [%]	Stratification 45sec [%]	Stratification 60sec [%]	Average stratification [%]	Stratification rating
PUM1	0.70 (240kg)	46	17	7.3	-	7.3	Poor
PUM2	1.16 (325kg)	43	19	5.9	9.4	7.6	Poor
PUM3	1.16 (270kg)	37	17	11.4	11.3	11.3	Moderate
PUM4	1.16 (290kg)	39	18	10.3	11.9	11.1	Moderate
PUM5	1.16 (300kg)	43	25	15.4	16.5	16	Good
PUM6	1.16 (310kg)	43	13	10.8	14.8	12.8	Mod / Good
PUM7	1.16 (310kg)	45	14	13.9	15.9	14.9	Mod / Good
PUM8	1.53 (400kg)	44	15	11	10	10.5	Moderate
PUM9	1.53 (450kg)	48	12	13	13.1	13.1	Mod / Good
PUM10	1.70 (560kg)	51	12	10.6	8.8	9.7	Poor
PUM11	1.70 (560kg)	51	12	8	7	7.5	Poor

For the PUM mixes, the stratification was measured on cylinders vibrated for 45 and 60seconds. The average value of these two measurements was used to calculate the stratification coefficient to estimate the ability of the mix to stratify. Generally the mixes were stratified better when vibrated for a longer time. Some of the mixes had a poorer stratification with longer vibration time. Possible explanations are; more trapped lightweight material within the structural layer and inconsistencies in batching or mixing the concrete.

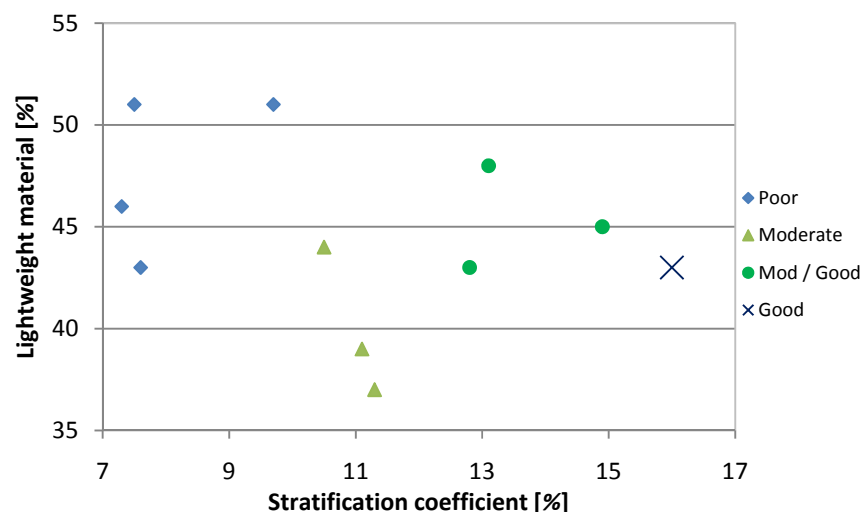


Figure 5.14 – Stratification coefficients for PUM mixes

The PUM mixes can be expected to have, according to Figure 5.14:

- Poor stratification, if the stratification coefficient is below than 10%
- Moderate stratification, if the stratification coefficient is between 10 and 12%
- Moderate to good stratification, if the stratification coefficient is between 12 and 15%

- Good stratification, if the stratification coefficient is above than 15%

The amount of light- and heavyweight material within the mix was not found to influence the location of the centre of gravity. This can be seen on Figure 5.14 where no trend was established between the stratification coefficient and the volume percent of lightweight material. The volume percent of lightweight material was calculated by using different relative densities for the pumice, as can be seen in Table 5.5. The relative densities and the volume of lightweight material are presented as the ones used when designing the mixes.

Table 5.6 – Stratification of the GB and BB mix cylinders

Mix	Lightweight [%]	Heavyweight [%]	Stratification 30sec [%]	Stratification 45sec [%]	Stratification Average [%]	Stratification rating
GB1	37	19	13.8	18.5	16.1	Moderate
GB2	36	19	19.4	21.0	20.2	Moderate
GB3	39	16	21.3	22.0	21.6	Moderate
GB4	39	16	19.4	23.3	21.3	Mod / Good
GB5	40	16	22.3	24.0	23.1	Mod / Good
GB6	42	17	23.4	26.1	24.8	Good
GB7	42	17	17.9	25.0	21.5	Moderate
GB8	45	15	24.0	26.1	25.0	Good
GB9	44	14	20.7	27.0	23.9	Good
BB1	46	17	8.9	11.6	10.3	Poor
BB2	44	17	-	15.2	15.2	Poor
BB3	45	16	-	-	-	Poor
BB4	43	17	22.0	26.5	24.3	Good
BB5	41	17	27.7	28.8	28.3	Good
BB6	40	18	27.0	26.9	26.9	Good

As listed in Table 5.6, for the GB and BB mixes, the stratification was measured on cylinders vibrated for 30 and 45seconds. The average value of these two measurements was used to calculate the stratification coefficient to estimate the ability of the mix to stratify. Generally a better stratification was gained when vibrated for a longer time. Although, mix BB6 had slightly lower stratification percent after 45seconds vibration, which could be because of good stratification already reached after 30seconds. Other possible explanations for this can be because of more trapped lightweight material located within the structural layer and inconsistencies in batching or mixing the concrete.

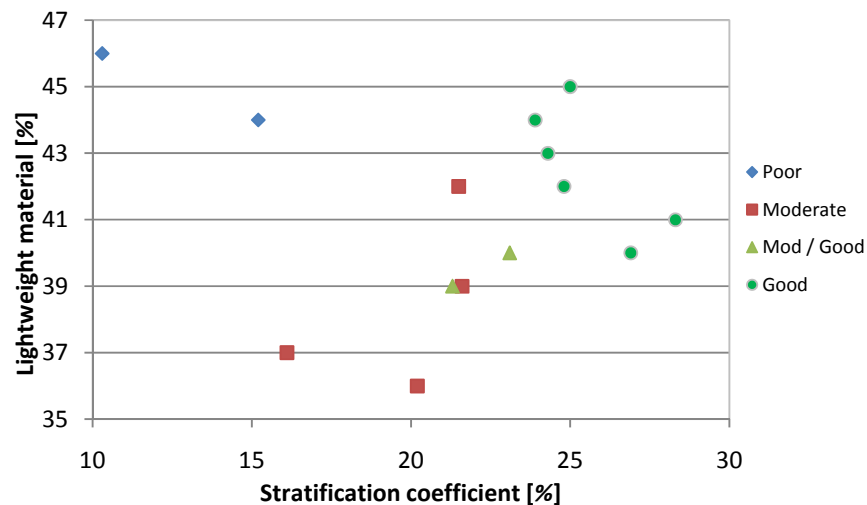


Figure 5.15 – Average stratification of cylinders cast from expanded glass beads mixes

The GB and BB mixes can be expected to have, according to Figure 5.15:

- Poor stratification, if the stratification coefficient is below than 16%
- Moderate stratification, if the stratification coefficient is between 16 and 24%
- Good stratification, if the stratification coefficient is above than 24%

This method gives good indication of the degree of stratification of hardened samples. The main disadvantages with using this method are:

- New mixes containing new materials have to be tested to find the stratification coefficient ranges
- When casting a panel or other large scale members, slices need to be cut off and measured to be able to assess the stratification coefficient

5.2.3 Consistency of layers

When casting the GB panels, an inconsistency was noticed in the layer thicknesses when the panels were cut, Figure 5.16, Figure 5.17 and Figure 5.18.

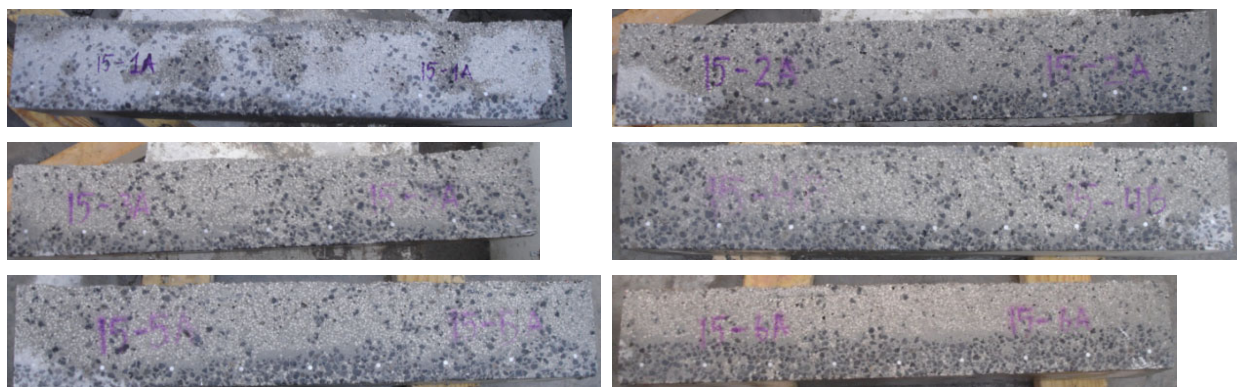


Figure 5.16 – Strips from panel PC-GB15 vibrated for 15seconds, slightly uneven material distribution



Figure 5.17 – Strips from panel PC-GB45 vibrated for 45seconds, uneven material distribution



Figure 5.18 – Strips from panel PC-GB30 vibrated for 30seconds, slightly uneven material distribution

The most likely explanation for this is that the mixes were too wet, causing them to start segregating within the mixer. Another possible explanation was an inconsistency in the vibrating amplitude across the vibrating table. The acceleration was therefore measured at 9 points on the vibrating table, as displayed on Figure 5.19, where the z axis is vertical to the table and the y axis is horizontal along the table. This test procedure was carried out by Mackechnie at the University of Canterbury.⁹ The maximum difference in acceleration at points along the vibrating table varied between 1.8g-7.3g. The maximum difference in acceleration at each point was measured from figures similar to Figure 5.20, which shows the measured acceleration for point A in the y-direction.

⁹ Mackechnie, J.R. 2007

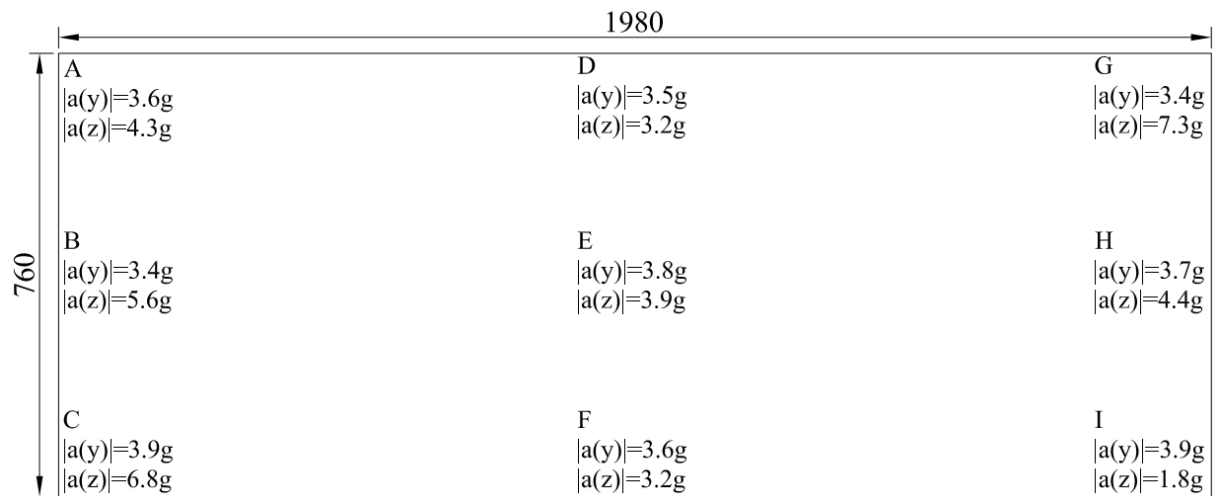


Figure 5.19 – Measured acceleration on 9 points along the vibrating table used

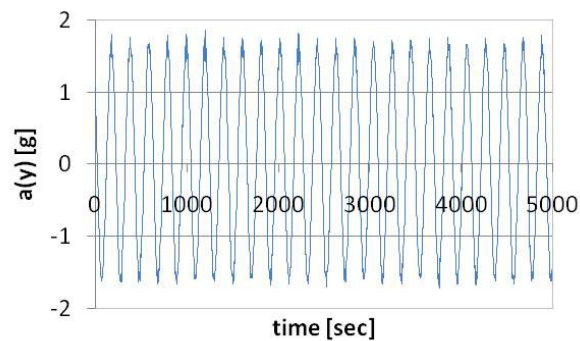


Figure 5.20 – Typical measured acceleration in y direction at point A on the vibrating table

Six cylinders were cast and vibrated at points A, C, D, F, G and I, to estimate the difference in stratification depending on the vibration acceleration, as displayed on Figure 5.21 and listed in Table 5.7. The amount of stratification was estimated by calculating the stratification coefficient. This was performed by James Mackechnie at the University of Canterbury.¹⁰



Figure 5.21 – Cylinders vibrated at different points on the vibrating table

¹⁰ Mackechnie, J.R. 2007

Table 5.7 – Measured acceleration on the vibrating table and stratification coefficient of cast cylinders

Sample	Point on table	Total horizontal acceleration	Total vertical acceleration	Stratification coefficient [%]
1	A	3.6g	4.3g	22.7
	B	3.4g	5.6g	
2	C	3.9g	6.8g	21.8
3	D	3.5g	3.2g	20.6
	E	3.8g	3.9g	
4	F	3.6g	3.2g	19.6
5	G	3.4g	7.3g	22.4
	H	3.7g	4.4g	
6	I	3.9g	1.8g	19.0

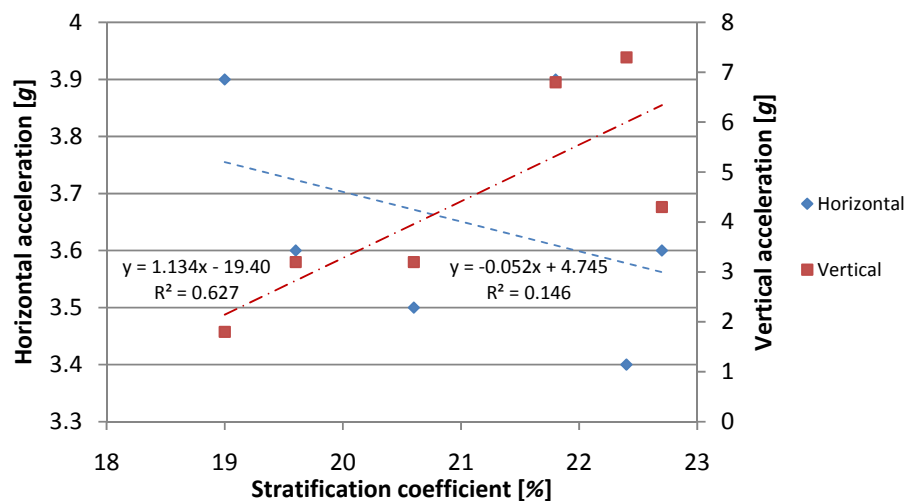


Figure 5.22 – The relationship between the stratification coefficient and the intensity of the acceleration

The stratification coefficient of the cylinders varied from 19.0-22.7%. The relationship between stratification coefficient and horizontal and vertical acceleration is displayed in Figure 5.22. The figure shows a clear trend between the stratification coefficient and the vertical acceleration. The proportion of heavyweight material in the cylinders was not consistent, making the comparison of the stratification less reliable, but all cylinders were well stratified. No relationship was found between the horizontal acceleration and the stratification coefficient, but the effect is hard to find on the cylinders as the diameter was only 100mm. In Figure 5.21, the effect of the horizontal acceleration can be seen on the cylinder vibrated at point I, as the material has clearly shifted to the right. When casting big panels, the difference found in the horizontal acceleration should be able to shift the material around within the panel.

The uneven layer thickness of the panels can therefore both be explained by:

- The fact that the mix was too wet and starting to segregate within the mixer
- Inconsistent levels of vibration effort on the vibrating table

5.3 Conclusion

When assessing the fresh properties it was hoped that the slump flow would give an indication of the stratification potential. For the concrete to be able to stratify it had to have a slump flow within a defined range, but stratification could not be guaranteed. If the slump flow was too low, the mix became too sticky to stratify, and if the slump flow got too high, the risk of segregation within the mixer or when being handled became significant.

Rheology provided better indication of the stratification potential, as defined rheological ranges indicated the stratification potentials. The yield shear stress and the plastic viscosity had to be relatively low to provide concrete that was flowable enough to allow proper stratification. A linear relationship was found between the yield shear stress and the plastic viscosity for the GB and BB mixes. This relationship indicated that to gain good stratification:

- The lower the plastic viscosity, the higher the yield shear stress can be
- The lower the yield shear stress, the higher the plastic viscosity can be

A relationship was not found for the PUM mixes most likely due to variability in the aggregate material properties.

The degree of stratification was found to be dependent on the intensity and time of vibration, which was optimized for various mix designs. The degree of stratification was assessed in both the fresh and hardened state. In the fresh state, a method measuring the penetration depth was developed without great success, while in the hardened state a stratification coefficient was calculated by finding the centre of mass of stratified cylinders. This second method was found to predict the degree of stratification well.

5.4 References

- Banfill, PFG, “The rheology of fresh cement and concrete – a review”, Proc. of 11th ICCI Conference, Durban, 2003, CSSA.
- Chia, Kok-Seng; Kho Chen-Chung & Zhang, M.H. 2005. Stability of Fresh Lightweight Aggregate Concrete under Vibration. ACI Materials Journal 102:347-354.
- Mackechnie, J.R. 2006. Lecture notes in ENCI 621, *Concrete Materials and Practice*, second semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007. “Stratified Precast Concrete Panels for Buildings.” *Concrete Plant International*, July 2007.
- Mackechnie, J.R.; Park, Y.S.; Sævarsdóttir, T & Bellamy, L. 2007. *Variable Density Precast Concrete Panel Development*. Unpublished paper. University of Canterbury, New Zealand.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Neville, A.M. 1995. “*Properties of Concrete*” Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- Roussel, N. 2006. *A theoretical frame to study stability of fresh concrete*. Materials and Structures 39:81-91.

6 Structural Performance

As the name suggests, variable density concrete panels have different properties within a given member. That is, structural concrete is used in the bottom third of the panels, while the remaining two thirds at the top are lightweight, insulating concrete. The major difference in hardened properties between the top and bottom layer are that the lightweight concrete has much lower strength, elastic modulus and density than the normal/heavyweight concrete in the bottom structural layer. To be able to use the variable density panel in practice the structural performance of the variable density concrete had to be examined.

To estimate the structural performance of the stratified panel, two types of samples were prepared using the same mix designs:

- **Control tests:** cylinders were measured for compression strength, elastic modulus and density of the heavier structural layer and the lightweight, insulating layer separately. The cylinders were cured and tested according to NZS 3112¹
- **Performance tests:** stratified strips were tested for axial compression and flexural tensile strength. The strips tested were mainly gained by cutting 1000x700x120mm variable density concrete panels into 650x150x120mm strips

Panels were cast with different aggregate and binder materials and cured under different conditions and had different amount of stratification as listed in Table 6.1.

Table 6.1 – Structural performance was tested on several samples using several mix designs & materials

Materials	Mix	Cylinders	Stratifi- cation	Mix	Panels curing	Stratification rating
PC 2-4 GB Perlite Slag	PC-GB3	Concrete stratified in a bucket and 200mm high cylinders cast	Good	PC-GB15	Wet cured for 7days at 21°C	Moderate
				PC-GB30		Good
				PC-GB45		Very good
	PC-GB1	500mm high cylinders cut down to 200mm high structural and lightweight cylinders	Poor	PC-GB	Wet cured for 7days at 21°C and then exposed to outdoor conditions for 5 months	Poor
	PC-GB2		Good			
PC Pumice Perlite GW	PC-PUM1*	500mm high cylinders cut down to 200mm high structural and lightweight cylinders	Poor	PC-PUM		Poor
	PC-PUM2		Poor/ Moderate			
PC 2-4 GB	PC-BB1**	Concrete stratified in a bucket and 200mm high cylinders cast	Good	PC-BB15	Wet cured for 7days at 21°C and then kept	Very good

¹ NZS 3112. 1986

Materials	Mix	Cylinders	Stratification	Mix	Panels curing	Stratification rating
0.5-1 GB Slag	PC-BB2		Good	PC-BB45	at 35°C temperature and 27% humidity for 80days	Very good
IPC 2-4 GB Perlite Slag	IPC-GB	Concrete stratified in a bucket and 200mm high cylinders cast	Good	IPC-GB	Heat cured at 60°C for 2days, covered in the lab till after 7days when placed to be exposed to outdoor conditions for 5 months	Very good
IPC Pumice Perlite GW	IPC-PUM		Good	IPC-PUM1		Very good
IPC 2-4 GB 0.5-1 GB Slag	-	-	-	IPC-BB1	Cured at ambient temperature for 7days and then kept at 35°C temperature and 27% humidity for 80days	Good
IPC Pumice 0.5-1 GB GW	-	-	-	IPC-PUM2		Moderate
IPC 2-4 GB 0.5-1 GB Slag	-	-	-	IPC-BB2	Heat cured at 60°C for 2days	Very good
				IPC-BB3		Very good

The materials are: PC – Portland cement; IPC – inorganic polymer cement; 2-4 GB – 2-4mm expanded glass beads; 0.5-1 GB – 0.5-1mm expanded glass beads; GW – greywacke chips

*Due to mistake when batching 8-13mm aggregate was used instead of 6mm stones

**The structural cylinders were not sufficient as they contained lightweight material at the top (crushed when tested)

***The lightweight cylinders were not sufficient; they were over vibrated and had started losing paste

There were a few extra strips that were tested for axial compression strength. These strips were cured for four months at 21°C and 50% humidity, changing to 35% humidity after that. The strips were broken 8 months after casting:

- Two strips were cast using the same mix design as for the PC-GB panel:
 - PC-GB-S – 120x120x470mm and 150x120x530mm
- Three strips were cast using the same mix design as for the PC-PUM:
 - PC-PUM-S – 2x120x120x470mm and 150x150x530mm

The inorganic polymer concrete panels were all cast by Mackechnie at the University of Canterbury² but tested and measured by Saevarsdottir.

6.1 Cylinder test results

Conventional 100Ø concrete cylinders were tested for compression strength, elastic modulus and density. These structural properties of the heavy/normalweight structural concrete and the lightweight insulating concrete were found separately as mentioned in the table above. The density, compression strength and elastic modulus results for all the cylinders tested are listed in Table 6.2. These can also be viewed on Figure 6.1, Figure 6.2 and Figure 6.3, where they are compared to the technical objectives set out for the stratified concrete after some initial trials. These technical objectives were:

- Compressive strength:
 - 2-5MPa for the lightweight concrete
 - 25-35MPa for the structural concrete
- Density:
 - 1000kg/m³ for the lightweight concrete
 - 2250 kg/m³ for the structural concrete

Table 6.2 – Material properties of the stratified concrete at 28days (mix PC-GB3 after 64days)

MIX		Theoretical Density [kg/m ³]	Actual Density [kg/m ³]	Compressive Strength [MPa]	Modulus of Elasticity [GPa]
PC-GB1	Lightweight	1305	1726	12.7	11.9
	Structural		1957	19.3	14.3
PC-GB2	Lightweight	1305	1404	8.8	6.4
	Structural		2388	22.4	20.7
PC-GB3*	Lightweight	1288	1305	8.7	9.4
	Structural		2178	30.4	30.2
PC-PUM1	Lightweight	1367	1851	21.5	13.0
	Structural		2211	21.7	18.2
PC-PUM2	Lightweight	1367	1680	10.5	8.4
	Structural		2169	19.6	18.1
PC-BB1**	Lightweight	1404	1122	5.0	7.5
	Structural		2353	19.7	-
PC-BB2***	Lightweight	1404	1018	3.3	3.4
	Structural		2456	24.1	29.5
IPC-GB	Lightweight		1280	9.5	4.5
	Structural		2095	14.0	8.0

² Mackechnie, J.R. 2007

MIX		Theoretical Density [kg/m^3]	Actual Density [kg/m^3]	Compressive Strength [MPa]	Modulus of Elasticity [GPa]
IPC-PUM	Lightweight		1230	7.5	5.5
	Structural		2100	15.0	11.0

*Tested after 64 days of curing

**The structural cylinder had lightweight material at the top, which crushed when being tested

***The lightweight cylinders were over vibrated lacking sufficient amount of paste

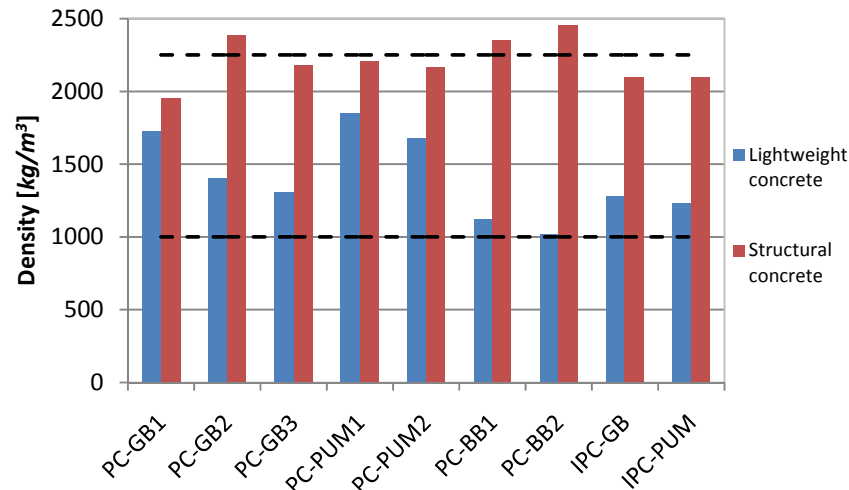


Figure 6.1 – Measured density of lightweight and structural concretes; aimed values were 1000 and 2250 kg/m^3

A ratio between 1.1 and 1.3 between the densities of the structural (bottom) and lightweight (top) concrete for the PC-GB1 and PC-PUM mixes indicate that these cylinders did not gain sufficient stratification. The ratio between the aimed values, 1000 kg/m^3 and 2250 kg/m^3 , is 2.3 but a ratio above 2.0 is only reached for two mixes, PC-BB1 and 2, cast from the same mix design containing Portland cement and two grades of expanded glass beads. The remaining ratios are between 1.6 and 1.7, mainly due to higher density of the lightweight concrete than what was aimed for. The densities of the structural concretes are close to the technical objective in most cases, as they are generally above 2000 kg/m^3 . The lightweight concrete is on the other hand too heavy, as PC-BB2 is the only mix where the cylinders reach the aimed value.

The varying densities within cylinders cast by using the same mix designs, PC-GB1 & 2 and PC-BB1 & 2 indicates:

- Inconsistency in casting:
 - Segregation or inhomogeneous material distribution when batching
 - Different amount of vibration and/or stratification
- Different amount of defects such as compaction voids and contamination

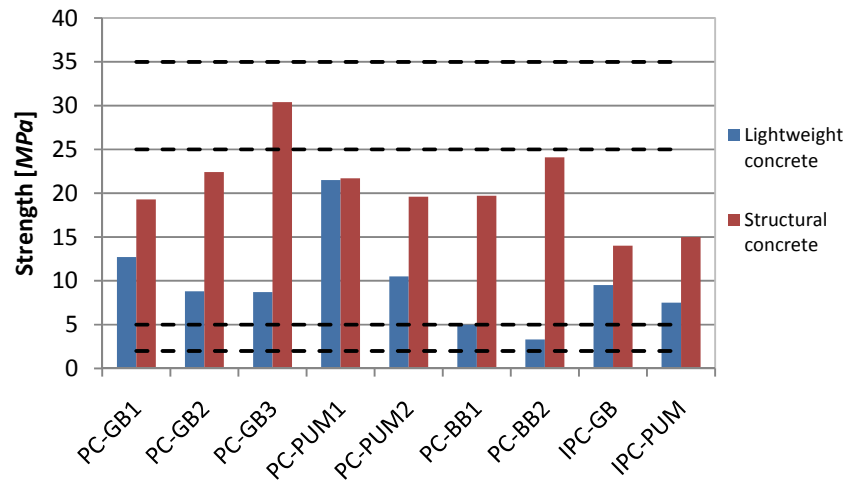


Figure 6.2 – Compression strength of lightweight & structural concretes; aimed values were between 2-5 & 25-35MPa

Structural concrete had lower compressive strength than what was aimed for, as PC-GB3 is the only mix providing sufficient compressive strength as shown in Figure 6.2. However these cylinders were however tested after 64days of curing, instead of 28days increasing the strength slightly. The low strength of the structural cylinders and the fact that there densities were too low indicates some amount of trapped lightweight material within the structural concrete.

Lightweight concrete was generally too strong, as PC-BB concrete was the only mix within the desired range but this concrete also had the lowest density. Structural concrete produced using inorganic polymer cement had significantly lower strength than the Portland cement ones but these mixes were not optimally formulated.

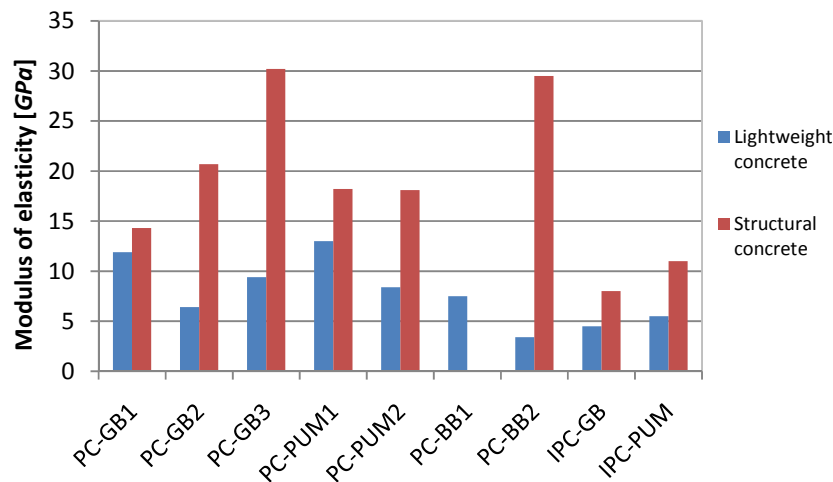


Figure 6.3 – Modulus of elasticity of the lightweight and structural concrete

The elastic modulus for the lightweight concrete varied from being 3.4-13.0GPa, with an average value of 7.8GPa when including the IPC-GB and IPC-PUM results, and 8.6GPa when excluding these. The elastic modulus on the other hand varied from being 14.3-30.2GPa for the structural concrete, with an average value of 18.8GPa when including the IPC-GB and IPC-

PUM results, and 21.8GPa for the Portland cement mixes only. This is a lower modulus of elasticity than what should be expected for light- and normalweight concretes as:

- According to Mindess et al.³ the modulus of elasticity for normalweight concrete is roughly between 20GPa and between $10\text{--}25\text{GPa}$ for lightweight concrete
- According to Eurocode (EC2)⁴ the secant modulus of elasticity (E_{cm}) is found by following equation:

$$E_{cm} = 9.5(f_{ck} + 8)^{1/3}$$

Where, f_{ck} is the characteristic cylinder compressive strength of concrete. This gives:

- Modulus of elasticity of 29GPa , for concrete with a compressive strength of 20MPa
- Modulus of elasticity of 27GPa , for concrete with a compressive strength of 15MPa
- Modulus of elasticity of 24GPa , for concrete with a compressive strength of 8MPa

The modulus of elasticity of the lightweight cylinder from mix PC-BB2 has some uncertainties as the concrete lacked paste, making it hard to place strain gauges. This could explain why it has significantly lower modulus of elasticity than the other lightweight cylinders gained from Portland cement mixes. For well stratified Portland cement cylinders, the structural concrete had between 3.2 to 3.9 times higher modulus of elasticity than the lightweight concrete, excluding results from PC-BB2. The modulus of elasticity for the inorganic polymer cement concretes was significantly lower than for the Portland cement ones, and the difference between the structural and lightweight concretes was significantly lower as well. This is related to the different nature of the cements being used.

In general, the structural concrete bottom cylinders were stronger, stiffer and heavier than the lightweight concrete top cylinders, and the difference increases the as the stratification coefficient increases. The hardened properties of these mixes are slightly different to what was aimed for as the density and strength of the lightweight concrete are higher, and the structural concrete has lower density and strength. This can be explained by some amount of trapped material within the wrong layers.

6.2 Strip test results

Most of the strips tested for flexural tensile and axial compression strength, were $650 \times 150 \times \sim 120\text{mm}$ produced by cutting $1000 \times 700 \times \sim 120\text{mm}$ stratified panels. Details of the panels and curing environments are given in Table 6.1. The strips produced from cutting the panels were able to sustain reasonable stresses in compression and bending, with typical test results being:

- $5.4 - 19.3\text{MPa}$, with an average value of 9.8MPa in compression
- $3.5 - 4.9\text{MPa}$, with an average value of 4.2MPa in ultimate flexure strength
- $1.4 - 4.5\text{MPa}$, with an average value of 2.3MPa in flexural strength when first cracking

6.2.1 Axial compression strength

To estimate the axial compression strength of a full scale panel, strips were tested in Avery universal testing machine, Model 7104 DCJ with 1000kN capacity. The strips were aligned

³ Mindess, S.; Young, J.F. & Darwin, D. 2003:428

⁴ Eibl, Josef. 1995:623

vertically, as columns, into the machine and a 1-2MPa load rate per minute was applied to the strips as shown on Figure 6.4.



Figure 6.4 – Testing machine used to get the axial compression strength of strips

The strength results from all the strips tested are listed in Table 6.3.

Table 6.3 – Axial compression strength [MPa] of strips

Mix	Compression strength [MPa]			Average
PC-GB	15.6	15.2	12.6	14.5
PC-PUM	15.9	21.6	20.5	19.3
IPC-GB	7.8	3.4	6.2	7.0
IPC-PUM1	9.2	9.8	8.6	9.2
PC-GB15	16.3	15.0	16.3**	15.9
PC-GB30	13.5	11.6*	10.8**	12.0
PC-GB45	7.5	6.5	7.5**	7.2
PC-BB15	6.4	5.8	5.9	6.0
PC-BB45	7.7	7.9	7.6	7.8
IPC-BB1	6.0	6.0	6.9	6.3
IPC-PUM2	10.1	10.5	10.0	10.2
IPC-BB2	4.9	5.5	5.6	5.4
IPC-BB3	6.4	6.9	6.8	6.7
PC-GB-S	19.6	19.4***		19.5
PC-PUM-S	29.1	30.0	11.5***	23.5

* This strip had uneven stratification

** Tested after 151days in the drying room

*** 150x120x530mm and 150x150x530mm strips

The axial compression strength for the panel strips was between 5.4-19.3MPa, with an overall average value of 9.8MPa. As listed in Table 6.3, the axial compression strength is generally between 5 and 10MPa. The cylinders that are not well stratified have higher strength as discussed later in this chapter. The lower limit of cylinder compressive strength of conventional concrete for residential purposes is 17MPa. As the variable density panel is 250mm thick with an average strength of 9.8MPa, this is comparable to a 144mm thick 17MPa conventional concrete wall as:

$$\sigma \text{ [MPa]} = \frac{F \text{ [N]}}{A \text{ [mm}^2\text{]}} \rightarrow \sigma_{var} \times t_{var} = \sigma_{con} \times t_{con} \rightarrow t_{con} = \frac{\sigma_{var} \times t_{var}}{\sigma_{con}}$$

$$t_{con} = \frac{9.8MPa \times 250mm}{17MPa} = 144mm$$

Where σ is the strength, F is force, A is area, con refers to conventional concrete and var to variable density concrete. The different systems can be compared assuming the variables changing between the variable density concrete panel and a conventional concrete panel are the strength and the thickness. Here it must be noticed that:

- For the conventional concrete panel, $17MPa$ is cylinder strength whereas for the variable concrete panel the axial compression strength is being used. That is, assuming short conventional concrete columns, where no reduction is made in load carrying capacity due to slenderness issues for the variable density concrete strips
- A large proportion of lightweight material is also going to reduce the load the panels need to carry, when compared to conventional concrete
- The variable density strips include $\varnothing 4 \times 75 \times 75mm$ steel mesh



Figure 6.5 – Failure modes of stratified concrete loaded in compression

The strips generally showed no signs of buckling but failed at the interface between the structural and insulating layers, as shown on Figure 6.5. There are some potential for increasing the strength, by using different materials and by controlling the stratification better. Using heavier and stronger lightweight aggregate particles does however affect the thermal properties, as it increases the thermal conductivity lowering the total R-value of the element.

6.2.2 *Flexural tensile strength*

To estimate the flexural tensile strength of a full scale panel, the strips were tested in Avery universal testing machine; model 7109 DCJ with $100kN$ capacity. The strips were placed horizontally with the structural layer on the bottom, like beams, and $1-2MPa$ load rate per minute applied to the strips as shown in Figure 6.6. On the same figure the apparatus used to measure the displacement when loading is also displayed, but the displacement of the strip was found by placing a small metal bar over the middle of the strips and the displacement of both ends was measured. The displacement of the strip is the average of the bar displacements.



Figure 6.6 – Testing machine used to get the flexural tensile strength and displacement of the strips

All strips include $\emptyset 4 \times 75 \times 75 \text{ mm}$ steel mesh in the bottom structural layer which starts contributing in load bearing when the concrete cracks. Strips do not break until the steel yields or fractures, resulting in similar ultimate strength for all the strips. The flexural strength of the concrete itself is found by the applied load when the first crack in the strip appears, found from the relationship between the displacement and the applied load. These relationships can be viewed in the appendixes in the end of the chapter. Table 6.4 gives details of the average flexural tensile strength and average flexural strength at first cracking for the different concrete mixes.

The displacement was generally less than 1 mm before the first crack appeared in the strips breaking in the middle. After that, the displacement and the load increased, until the strips failed at steel fracture as shown on Figure 6.7.



Figure 6.7 – General failure mode of strips after being tested for flexural tensile strength

Table 6.4 – Ultimate flexural strength and the flexural strength when the strips first crack

Mix	Flexural tensile strength [MPa]			Average	Flexural strength at first cracking [MPa]			Average
PC-GB	4.4	4.7	3.9	4.3	1.9	2.4	1.7	2.0
PC-PUM	5.0	4.9	4.7	4.9	2.3	2.2	2.3	2.3
IPC-GB	1.1	4.5	4.8	4.6	0.5	1.7	1.4	1.5
IPC-PUM1	4.5	4.0	4.6	4.4	1.8	1.8	1.6	1.8
PC-GB15	5.1	4.7	5.0	4.9	4.4	4.4	4.8	4.5
PC-GB30	4.4	4.6	4.3	4.4	3.6	3.4	3.6	3.5
PC-GB45	4.1	4.5	4.1	4.2	2.8	2.8	2.9	2.8
PC-BB15	1.8	4.1	3.8	4.0	1.1	1.7	1.2	1.5
PC-BB45	4.0	4.4	3.9	4.1	2.1	2.2	2.0	2.1
IPC-BB1*	1.2	0.4	0.6	0.7	-	-	-	-
IPC-PUM2*	0.9	0.8	0.6	0.8	-	-	-	-
IPC-BB2	3.5	1.5	0.9	3.5	1.6	0.5	0.4	1.6
IPC-BB3	2.1	3.6	3.6	3.6	0.9	1.4	1.3	1.4

*The strips failed close to the supports making it hard to estimate the flexural strength at first cracking as can be seen on Figure 6.21 and Figure 6.23

Generally strips failed in the middle, but there were some exceptions where failures occurred close to the support, due to shear cracking, as can be viewed on Figure 6.8. These can clearly be identified on the displacement versus applied load diagrams viewed in the appendices. Strips failing close to the support were:

- All the IPC-BB1
- All the IPC-PUM2
- Two IPC-BB2 strips
- One IPC-GB strip
- One IPC-BB3 strip
- One PC-BB15 strip

It must be noticed that ten off these eleven strips were cast using inorganic polymer cement mixes, which were poorly finished as their water content was too high also reducing their strength. These strips were not included when calculating the average flexural tensile strength.



Figure 6.8 – Strips failing close to the supports

As a general rule, it can be assumed that the tensile strength of concrete is 10% of its compressive strength, which is about the same strength⁵ provides:

$$f_{ctm} = 0.3 f_{ck}^{2/3}$$

⁵ Eibl, Josef. 1995:662-663.

Where f_{ctm} is the mean value of the tensile strength and f_{ck} is the characteristic cylinder compression strength of concrete. A comparison of the flexural tensile strength when the concrete cracks with the compression strength in Table 6.3, indicates good flexural strength compared to the axial compression strength. The flexural tensile strength is always higher than 10% of the axial compression strength, which should be lower than the cylinder compressive strength. Here it must be noticed that the strips were only tested having the structural bottom layer sitting on the support but not vice versa, that is, with the lightweight top layer sitting on the supports. That would significantly reduce the flexural strength of the strips.

6.3 Analysis of results

The strength of the variable density concrete was found to be affected by several parameters such as:

- The relative strength of the layers
- The degree of stratification
- Curing environment
- Relative thickness of the structural layers
- Amount of defects such as compaction voids and contamination

All these factors will be considered in following sections.

6.3.1 *Relative strength of layers*

Details of concrete strengths for each layer are shown in Table 6.2. Cylinder strengths were an indication of the likely strength in each layer of the stratified concrete. Cylinder strength is compared with the performance based strength; that is, the axial compression strength and flexural tensile strength at first cracking, shown in Figure 6.9 and Figure 6.10. The variable density concrete cylinder strength is calculated by using following equation:

$$f'_c(\text{variable density concrete}) = \frac{1}{3} f'_c(\text{structural}) + \frac{2}{3} f'_c(\text{lightweight})$$

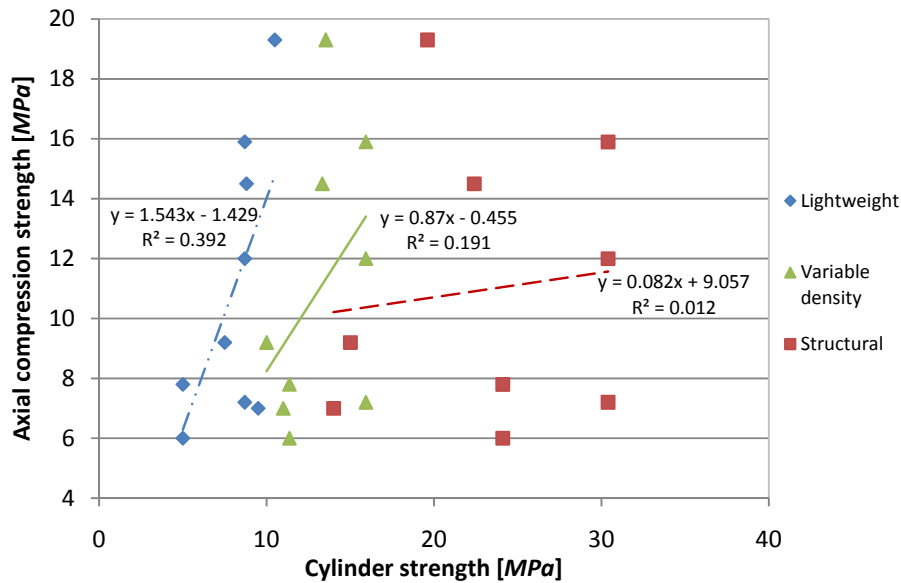


Figure 6.9 – Compression versus cylinder strength of lightweight, structural and variable density concrete

Analysis of Figure 6.9 indicates that there was no relationship found between the axial compression strength and the cylinder strength of the structural and the variable density concrete. Poor relationship was however found between the lightweight cylinder strength and the axial compression strength.

The axial compression strength of the strips was generally higher than the cylinder strength of the lightweight top cylinders, but considerably lower than the cylinder strength of the structural concrete cast using the same mix design,. There can be many reasons for this including:

- The interface layer in the strips is much weaker than a cylinder with even contribution of material and no interface layers
- The heavyweight material layer in the strips could have a higher proportion of trapped lightweight material than in the cylinders

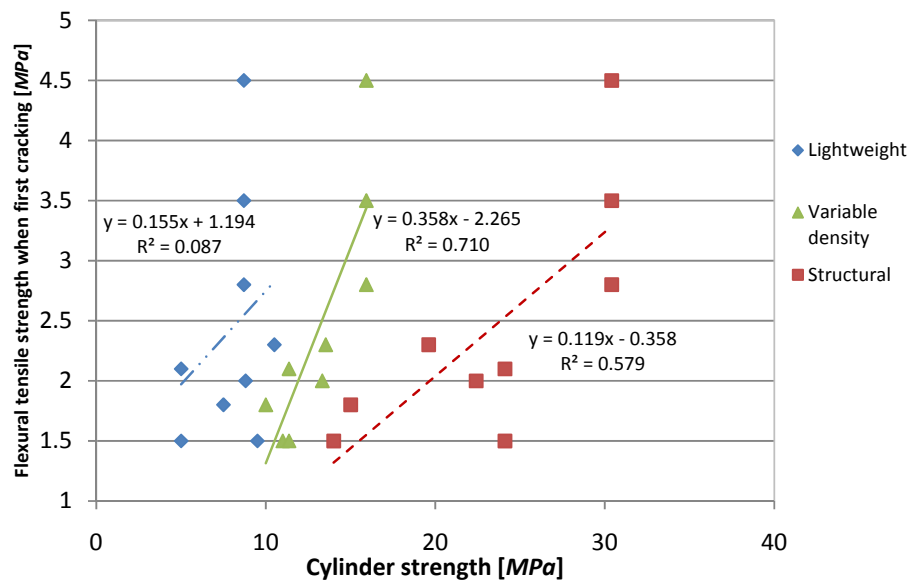


Figure 6.10 – Tensile versus cylinder strength of lightweight, structural and variable density concrete

When comparing the flexural strength at first cracking with the cylinder strength of the variable density and structural concrete, a clear trend was found as Figure 6.10 indicates. No relationship was found between the lightweight concrete cylinder strength and the flexural strength.

As all the strips contain a steel mesh, the axial compression strength can be influenced by the strength of the steel. This could explain why the relationship between the control and performance test is significantly weaker for the axial compression strength than for the flexural tensile strength at first cracking. As there are other factors such as degree of stratification of the strips, different curing of the cylinders and interfacial effects, a perfect relationship cannot be expected.

6.3.2 Degree of stratification

To estimate the effect the degree of stratification has on the structural performance of the variable density concrete panels, a comparison of panels PC-GB15, PC-GB30 and PC-GB45 was made, having stratification coefficient of 18.2%, 24.6% and 27.9% respectively. These panels were cast using the same mix design, cured under the same conditions and tested at the same time minimizing other factors that might affect the results. However, this was also the case for mixes GB-BB15 and GB-BB45, but these mixes did not have a significant difference in stratification coefficient or strength, making them harder to compare.

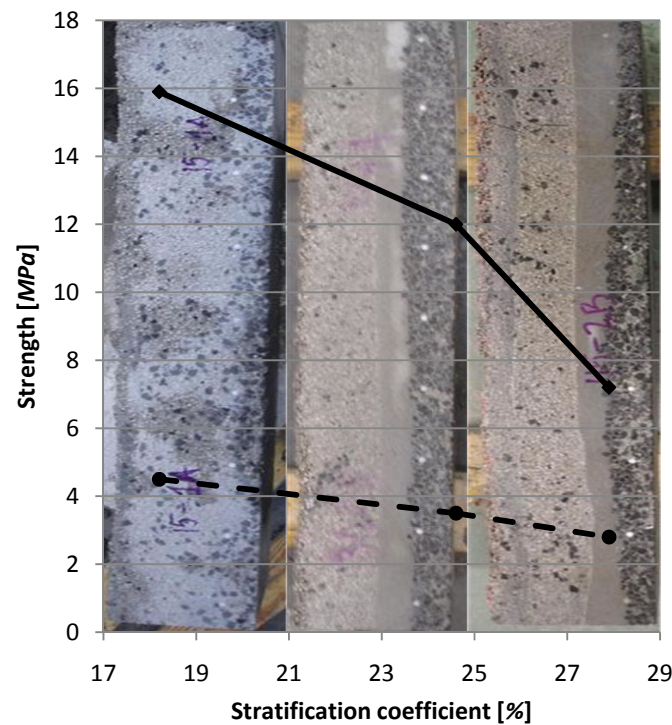


Figure 6.11 – Axial compression (solid) and flexural tensile strength (dashed) versus stratification coefficient

In Figure 6.11, the stratification coefficient for PC-GB15, 30 and 45 is plotted against the axial compression strength of the strips and the flexural tensile strength at first cracking. From the figure, it can be seen that well stratified samples had lower axial compressive and flexural tensile strength than more homogenous specimens. The axial compression strength decreases faster than the flexural tensile strength. When the concrete is homogenous there is no interface between the layers to cause weakness in the direction of principle stress. As the strips are vibrated more, the lightweight layer tends to lose paste that binds the lightweight particles together, and the paste starts building up between the lightweight and structural aggregate material. This causes the panels to have two interfaces between layers instead of one, but the interface between layers is the weakest part where the strips tend to break in axial compression.

6.3.3 Curing; age and procedure

On Figure 6.12, the axial compression, ultimate flexural tensile and flexural strength at first cracking are compared. These strips were cured in three different environments after a few days of initial curing as listed in Table 6.2, but these were:

- PC-GB, PC-PUM, IPC-GB and IPC-PUM1 – exposed to outdoor conditions for *5months*
- PC-GB15, PC-GB30 and PC-GB45 – only wet cured initially for *7days* before tested
- PC-BB15, PC-BB45, IPC-BB1 and IPC-PUM2 – kept at 35°C temperature and 27% humidity for *80days*
- IPC-BB2 and IPC-BB3 – cured at ambient temperature for approximately *30days*

It should be noted that these strips are produced from different mix design detailed in Table 6.2.

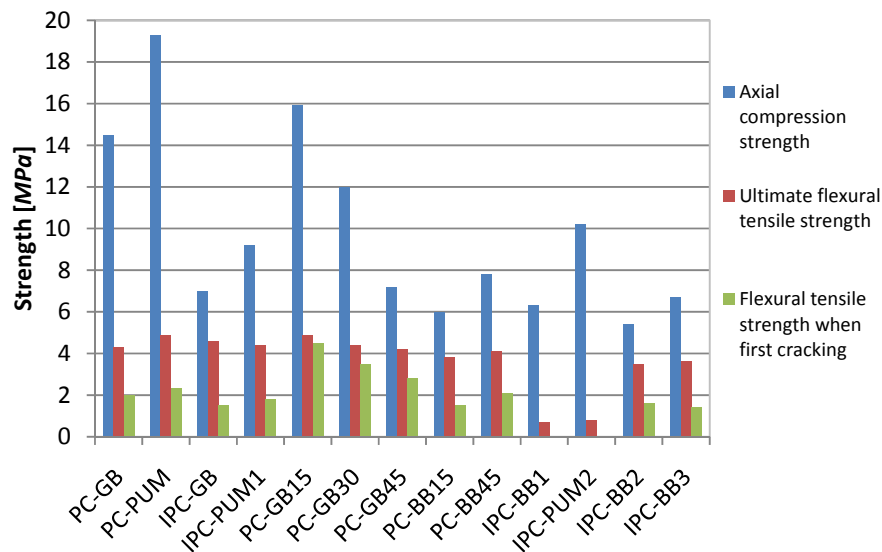


Figure 6.12 – Performance results for strips tested for axial compression and flexural tensile strength

The flexural tensile strength is higher for the strips tested after 7 days of wet curing (GB-PC15, 30 & 45) than the ones exposed for 5 months (PC-GB, PC-PUM, IPC-GB and IPC-PUM). This could be related to some longer term effects and drying stresses. It is believed that the lightweight layer creeps to follow the deformations that occur in the structural layer, which should decrease the strength of the concrete.

The axial compressive strength did not seem to be affected by the curing as PC-GB had higher strength than the PC-GB15, 30 and 45 ones. But as mentioned before, the degree of stratification plays a significant role in determining the axial compression strength of variable density concrete. Strips PC-GB only had a stratification coefficient of 12.7% whereas PC-GB15 had a coefficient of 18.2%. This could explain the higher axial compression strength of PC-GB than of PC-GB15.

The strips that were cured in a hot dry environment, (PC-BB15 & 45, IPC-BB1 & IPC-PUM2), had lower strength than the strips mentioned before, but these contained different materials. This indicates that the drying rate affects the strength of the concrete; that is, the faster the concrete is dried the less strength it has, this is most likely because of less hydration of the cement.

In Figure 6.12, results can be summarised as follows:

- Mixes containing pumice generally have higher strength than mixes containing expanded glass beads, due to pumice being denser and stronger than the expanded glass beads
- Mixes containing inorganic polymer cement tend to have lower axial compressive strength than mixes containing Portland cement, but the inorganic polymer cement mixes were not optimally formulated

6.3.4 **Relative thickness of structural layers**

One of the factors that could be affecting the strength of the strips is the relative thickness of the structural layer. Strips GB-BB15 and 45 had significantly lower strength than mixes PC-GB15,

30 and 45 and when looking for possible explanations the amount of heavy- and lightweight material was examined:

- Mixes PC-BB15 and 45 – 40% of lightweight and 18% of heavyweight material
- Mixes PC-GB15, 30 and 45 – 44% of lightweight and 14% of heavyweight material

The stronger PC-GB15, 30 and 45 mixes therefore have a smaller proportion of heavyweight material but are still stronger. This indicates that there are other factors influencing the strength of these mixes, such as the lightweight aggregates being used or different curing of these strips as discussed earlier.

One way to increase the strength should be to increase the thickness of the structural layer which initially was set to be 80mm. By increasing the thickness of the structural layer to 100mm and decreasing the thickness of the lightweight layer to 150mm, the cylinder strength of the variable density concrete should be increased by approximately 7.6%. This was found by calculating the cylinder strength using:

$$f'_c(\text{variable density concrete}) = \frac{2}{5} f'_c(\text{structural}) + \frac{3}{5} f'_c(\text{lightweight})$$

Instead of:

$$f'_c(\text{variable density concrete}) = \frac{1}{3} f'_c(\text{structural}) + \frac{2}{3} f'_c(\text{lightweight})$$

This was done for all the mixes and the average increase in strength found to be 7.6%. Once the initial aims are reached, that is, having the cylinder strength of the lightweight concrete 5MPa and the structural concrete 25MPa, this should increase the strength by 11.4%. By increasing the thickness of the structural layer and decreasing the thickness of the lightweight layer, the thermal properties of the concrete is going to decrease, as the thickness of these layers was estimated to optimise the thermal performance of the variable density panel. Another possibility is to increase the overall thickness which should have similar effect.

6.3.5 Amount of defects; compaction voids and contamination

The strength of concrete is highly affected by the degree of compaction and the homogeneity of the material. That is, defects such as compaction voids and contamination of trapped material affects the strength of the variable density concrete as the material loses its homogeneity. This was found to be the case in the structural layer, as large amount of trapped lightweight material had negative effects on the strength of this layer.

When testing the strips for flexural tensile strength, some broke near the support indicating some inconsistencies in the material properties or weakness through the sample, possibly caused by a large contamination of lightweight material at one side of the strips due to compaction voids. This type of failure generally happened in the inorganic polymer cement concretes which are stickier than the Portland cement mixes making them harder to compact properly.

6.4 Conclusion and summary

Concrete in the structural layer was stronger, stiffer and heavier than the lightweight concrete but the difference depends on the materials being used. Hardened properties of these mixes were somewhat different to what was aimed for with the density and strength of the lightweight concrete higher and the structural concrete had lower density and strength.

Testing of strips cut from the panels produced reasonable performance, which can be summarised as follows:

- 5.4 – 19.3MPa, with an average value of 9.8MPa in compression
- 3.5 – 4.9MPa, with an average value of 4.2MPa in ultimate flexure strength
- 1.4 – 4.5MPa, with an average value of 2.3MPa in flexural strength at first cracking

There should be adequate strength capacity for likely service conditions, as the system should be able to withstand at least the same load as a 144mm thick panel made with 17MPa conventional concrete. The biggest structural issue for these panels is likely to be handling loads at early ages which were not assessed here.

The strength of the variable density concrete was found to be affected by several factors which are discussed below.

Relative strength of the layers – a relationship was found between the flexural tensile strength of the strips and the variable density cylinder strength, but this was not the case for the axial compression strength. Further investigation is therefore needed to find a suitable control test simulating the performance of the variable density concrete panels.

Degree of stratification – the strength of the variable density concrete decreases as the stratification coefficient increases. The axial compression strength decreases faster than the flexural tensile strength probably due to the fact that when the concrete was homogenous there was no interface between the layers which is the weakest part in the specimen.

Curing environment – the drying rate was found to affect the strength of the concrete. The faster the concrete dried, the less strength it was likely to have, due to less hydration of the cement.

Relative thickness of the structural layers – as the thickness of the structural layer was increased, the overall strength of the variable density strips increased.

Amount of defects such as compaction voids and contamination – strength of concrete was highly affected by the degree of its compaction and the homogeneity of the material. Trapped lightweight material was found to affect the strength of the structural layer in the variable density concrete.

6.5 References

- Eibl, Josef. 1995. Concrete Structures Euro-Design Handbook. Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH, Berlin, Germany.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Mindess, Sidney; Young, J. Francis; Darwin, David. 2003. *Concrete*. Second Edition. Pearson Education, Upper Saddle River, New Jersey.
- NZS, New Zealand Standard. 1986. “*NZS 3112: Method of Testing Concrete*”. NZS, New Zealand Standard, Wellington, New Zealand.

6.6 Appendixes

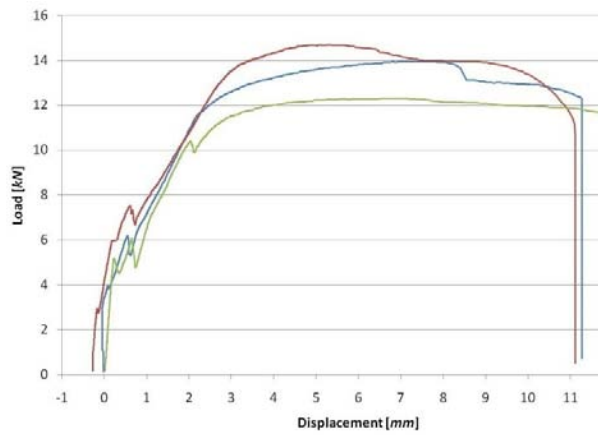


Figure 6.13 – PC-GB

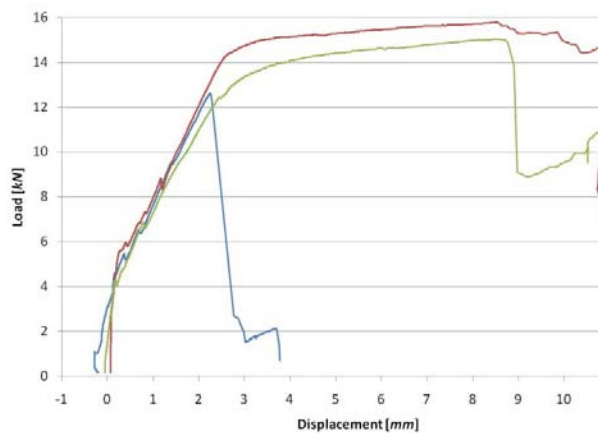


Figure 6.14 – IPC-GB

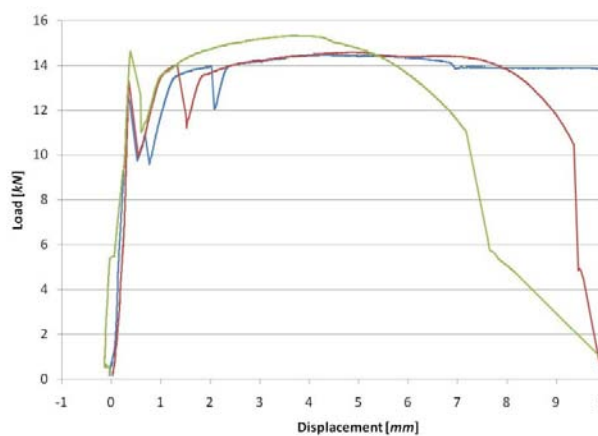


Figure 6.15 – PC-GB15

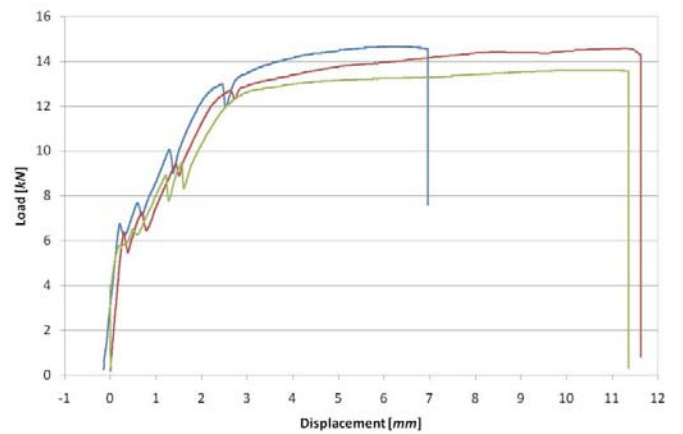


Figure 6.16 – PC-PUM

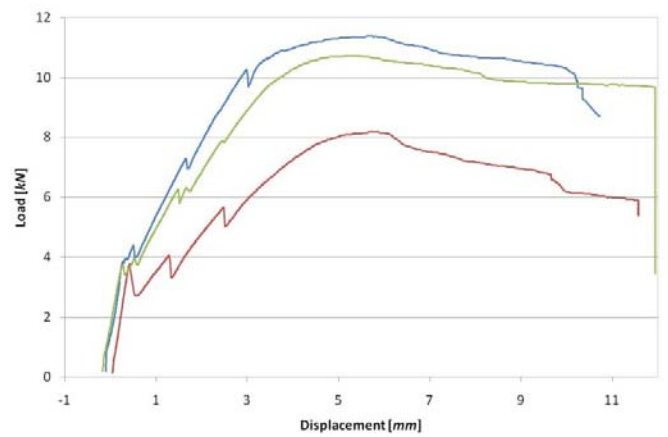


Figure 6.17 – IPC-PUM

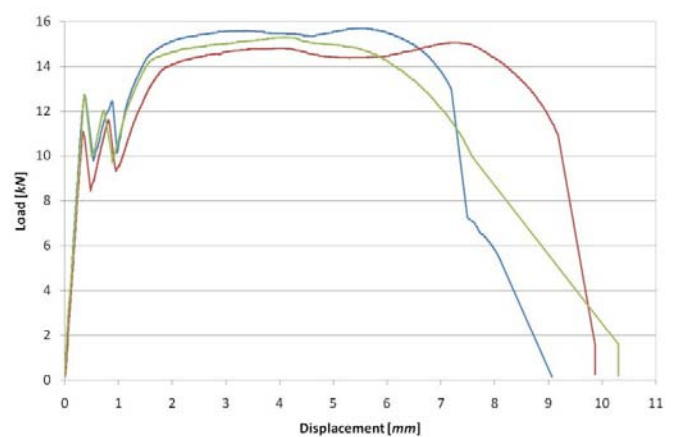


Figure 6.18 – PC-GB30

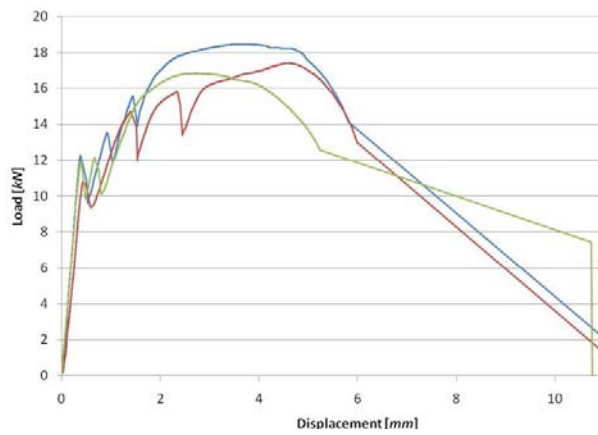


Figure 6.19 – PC-GB45

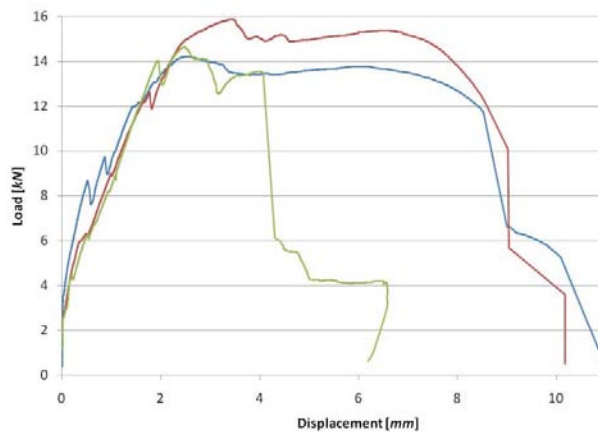


Figure 6.20 – PC-BB15

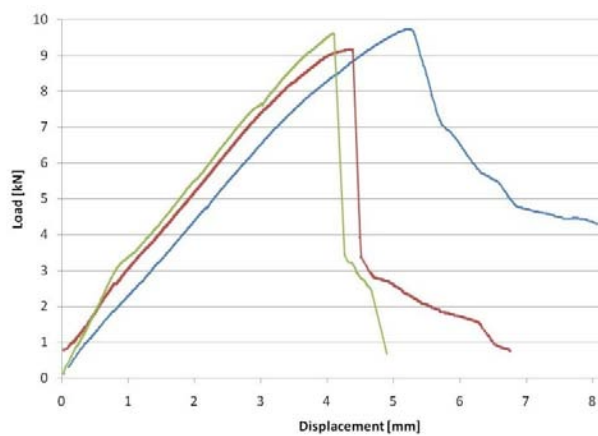


Figure 6.21 – IPC-BB1

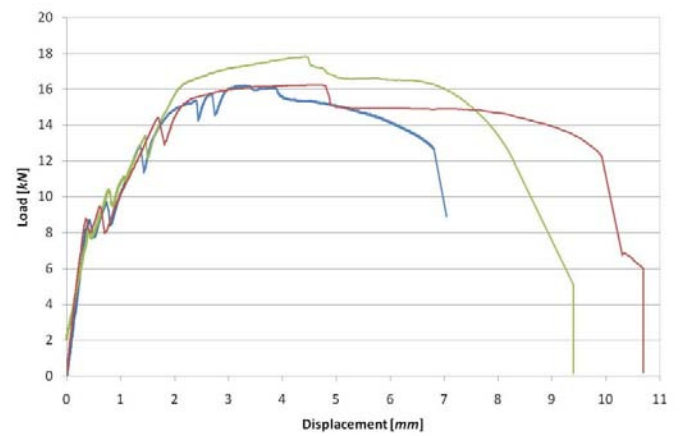


Figure 6.22 – PC-BB45

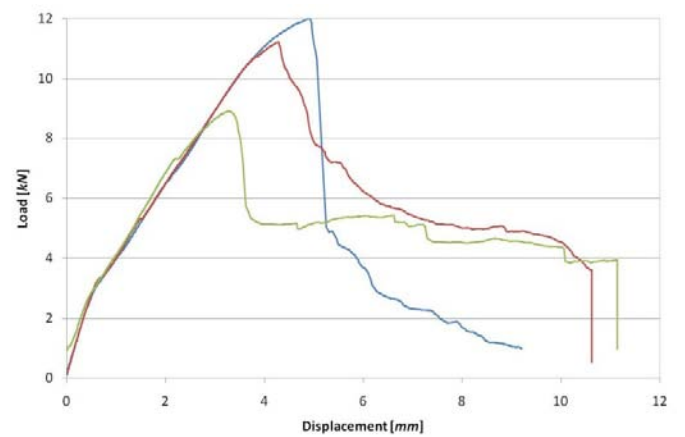


Figure 6.23 – IPC-PUM2

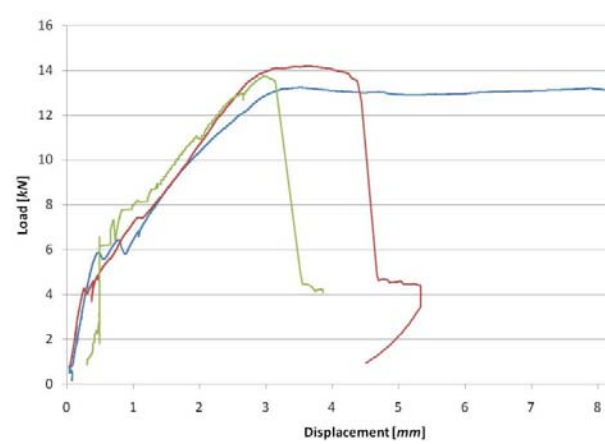


Figure 6.24 – IPC-BB2

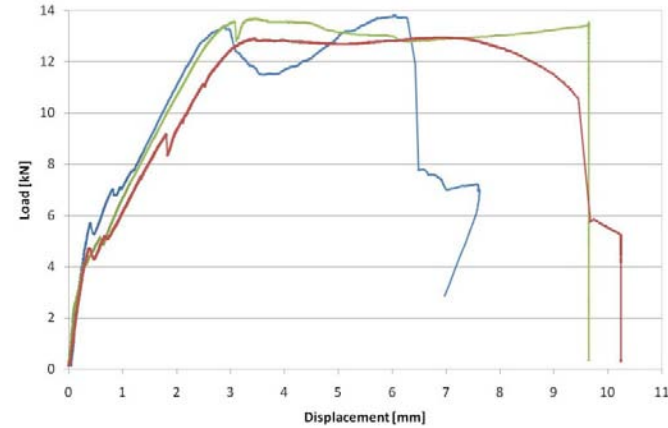


Figure 6.25 - IPC-BB3

7 Serviceability Performance

One of the main issues expected to affect the serviceability of the panels is related to differential shrinkage within the member, causing it to curl (warp). Differential shrinkage within a member can be caused by various reasons but the most common ones are different temperatures, moisture, stiffness (elastic modulus) or strengths.¹ As can be seen in Figure 7.1, all these situations can be expected within the panel. The top layer shrinks more than the bottom one as well as having lower strength and stiffness. The potential for warping in service is increased if the outside, top layer is exposed to more severe drying than the interior bottom layer.

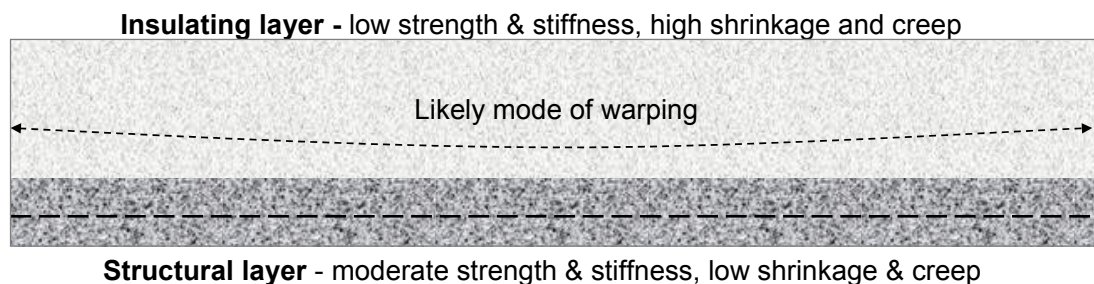


Figure 7.1 - Potential for warping of stratified concrete²

Shrinkage and warping were measured to evaluate the serviceability performance of stratified concrete in service. As differential shrinkage is the main cause for a member to warp, the shrinkage was measured for the structural and lightweight concrete from the stratified concrete separately.

To measure the warping, several variable density concrete specimens were cast, either strips or panels, using various materials and mix designs, and with different amount of stratification. A description of measured specimens is listed in Table 7.1. All the warping samples had a Ø4x75x75mm steel mesh in the bottom, structural layer with 20mm cover. To simulate the moisture loss experienced in a wall panel, the stratified sides were sealed to prevent any moisture loss from them, since a wall panel only loses moisture through the inside and outside surfaces. The samples were stored standing vertically like wall units, with the same end on the bottom and top the whole time.

¹ Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000

² Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

Table 7.1 – The Serviceability was tested on several samples using several mix designs & materials

Materials	Shrinkage Mix	Warping Mix	Sample	Panels curing	Stratification rating
PC 2-4 GB Perlite Slag	PC-GB2**	PC-GB15	650x150x120mm strip	Wet cured for 7days at 21°C and stored at 21°C and 50% humidity, changing to 35% after a month	Moderate
		PC-GB30	650x150x120mm strip		Good
		PC-GB45	650x150x120mm strip		Very good
	PC-GB1	PC-GB	Panel	Wet cured for 7days at 21°C and then exposed to outdoor conditions for 5 months	Poor
PC Pumice Perlite GW	PC-PUM1* PC-PUM2	PC-PUM	Panel		Poor
PC 2-4 GB 0.5-1 GB Slag	PC-BB1*** PC-BB2****	PC-BB15	Panel	Wet cured for 7days at 21°C and then kept at 35°C temperature and 27% humidity for 80days (panels) and 60days (strips)	Very good
		PC-BB45	Panel		Very good
		PC-2BB15S	1350x80x120mm strip		Moderate
		PC-2BB30S	1350x80x120mm strip		Good
		PC-2BB45S	1350x80x120mm strip		Very good
Low/high shrinkage	LS	LS-HS	1350x80x120mm strip		Good
	HS				
IPC 2-4 GB Perlite Slag	IPC-GB	IPC-GB	Panel	Heat cured at 60°C for 2days, covered in the lab till after 7days when placed to be exposed to outdoor conditions for 5 months	Very good
IPC Pumice Perlite GW	IPC-PUM	IPC-PUM1	Panel		Very good
IPC 2-4 GB 0.5-1 GB Slag	-	IPC-BB1	Panel	Cured at ambient temperature for 28days and then kept at 35°C temperature and 27% humidity for 80days	Good
IPC Pumice 0.5-1 GB GW	-	IPC-PUM2	Panel		Moderate

Materials	Shrinkage Mix	Warping Mix	Sample	Panels curing	Stratification rating
PC 2-4 GB Perlite Slag	PC-GB1	PC-GB1	120x120x470mm strip	Wet cured for 7days at 21°C and stored at 21°C and 50% humidity, changing to 35% after four months	Good
		PC-GB2	150x120x530mm strip		Good
PC	PC-PUM1*	PC-PUM1	120x120x470mm strip		Mod/Good
Pumice		PC-PUM2	120x120x470mm strip		Mod/Good
Perlite GW	PC-PUM2	PC-PUM3	150x150x530mm strip		Mod/Good

The materials are: PC – Portland cement; IPC – inorganic polymer cement; 2-4 GB – 2-4mm expanded glass beads; 0.5-1 GB – 0.5-1mm expanded glass beads; GW – greywacke chips

*Due to mistake when batching 8-13mm aggregate was used instead of 6mm stones

** After 44days of drying samples were placed in 21°C and relative humidity of 32-42% (average 35%)

***The lightweight prisms were over vibrated and lacking paste. Stored at 21°C and relative humidity of 32-42% (av. 35%)

****Initial measurement taken after 10days of wet curing. Stored in a humidity chamber, where after 7days 23°C where increased to 25°C as the evaporation rate was not high enough

7.1 Drying Shrinkage

Shrinkage prisms, 75x75x280mm, were cast by stratifying the concrete in a bucket before placing the structural and lightweight concrete separately into steel moulds. After approximately 24hours the samples were demoulded and placed in a fog room at 21°C for 7days. The samples were then placed in a drying room with 23°C and 50% humidity, and the shrinkage measured at regular intervals until 56days of drying.

In three cases, the standard curing according to AS 1012³, was not done:

- Prisms cast from PC-GB2 were moved to a different drying room after 44days of drying. The temperature in that room was 21°C and the relative humidity varied between 32-42%, with an average humidity of 35% instead of 50%
- Prisms cast from PC-BB1 were stored in a room with 21°C temperature instead of 23°C and a relative humidity varying from 32 to 42%, with an average humidity of 35% instead of 50%
- The initial measurements of prisms cast from PC-BB2, were taken after wet curing the samples for 10days, instead of 7days. The samples were stored in a humidity chamber where the temperature was increased to 25°C after 7days as the evaporation rate was not high enough, being under the minimum requirement of 7mL per 24hours

The 28 and 56days shrinkage results are listed in Table 7.2.

³ AS 1012. 1992

Table 7.2 – Measured shrinkage in the lightweight and structural concrete after 28 and 56days

MIX		28days [microstrain]	Ratio	56days [microstrain]	Ratio	W/B ratio
PC-GB1	Lightweight	1331	2.1	1724	1.9	0.68
	Structural	643		891		
PC-GB2	Lightweight	1133	2.2	1454	2.2	0.60
	Structural	509		647		
PC-PUM1	Lightweight	1561	2.6	1957	2.7	0.47
	Structural	611		714		
PC-PUM2	Lightweight	1345	1.7	1781	2.0	0.47
	Structural	776		900		
PC-BB1*	Lightweight	528	1.2	945	1.8	0.62
	Structural	436		520		
PC-BB2	Lightweight	395	0.8	1003	1.3	0.62
	Structural	493		745		
IPC-GB	Lightweight	607	1.8	863	2.0	
	Structural	331		429		
IPC-PUM	Lightweight	455	1.3	647	1.5	
	Structural	343		445		
LS-HS**	High shrinkage	863	1.9	1128	1.8	0.60
	Low shrinkage	456		627		0.47

* Lightweight prisms were over vibrated and lacked cement paste

** LS low shrinkage concrete and HS high shrinkage concrete discussed in chapter 7.1.1

Where shrinkage measurements deviated from the rest of the shrinkage measurements, or measurements were missing at 28 or 56days, a linear relationship was drawn between the nearest points. This occurred as follows:

- For mix PC-GB2, measurements taken at 44days for the lightweight concrete
- For mix PC-GB2, measurements taken at 56days were lost
- For mix PC-PUM1, measurements taken at 56days for the structural concrete
- For mix PC-PUM2, measurements taken at 56days for the lightweight concrete
- For mix PC-BB2, measurements taken at 28days were lost
- For mix LS-HS, measurements taken at 28days were lost

Two major reasons for these discrepancies were:

- The measurement instrument is sensitive and incorrect readings are possible
- The drying environment fluctuated outside of the normal range

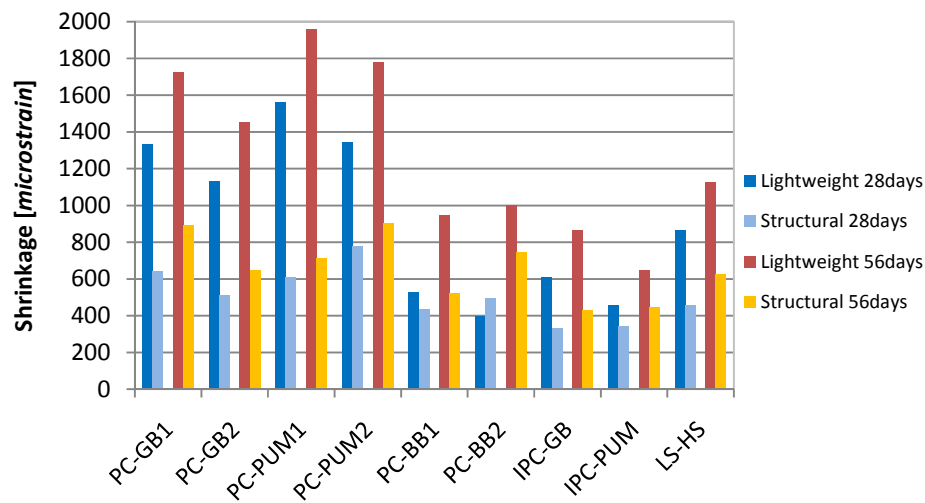


Figure 7.2 – Comparison of the shrinkage experienced between different mixes

Drying shrinkage of lightweight concrete was typically twice that measured in the structural concrete. The difference in shrinkage is dependent on the materials and mix design being used:

- Inorganic polymer concretes had lower shrinkage than Portland cement concrete, but the difference in shrinkage is of the same order
- Higher water binder ratios for mixes containing the same materials increased the shrinkage in both lightweight and structural concrete
- Using larger aggregate particles, PC-PUM, increased the shrinkage in the lightweight layer but decreased the shrinkage in the structural layer. This increases the shrinkage ratio between the lightweight and structural concrete
- Using a fine grade expanded glass beads instead of perlite as lightweight aggregate filler decreases the amount of shrinkage significantly in both concretes. This can be explained by the movement of water from the highly absorptive, saturated aggregate into the hydrating mortar. The difference in shrinkage between the two lightweight concrete mixes may be due to a different rate of water movement out of the aggregate particles⁴
- The structural concrete cast from the Portland cement mixes containing two grades of expanded glass beads (PC-BB1&2) experienced higher initial shrinkage than the lightweight concrete. This can again be explained by the movement of water from the highly absorptive, saturated aggregate into the hydrating mortar. After 14days of drying PC-BB1, the lightweight concrete had shrunk more than the structural concrete. This is not the case for PC-BB2, where after 28days of drying the lightweight concrete had still shrunk less than the structural concrete. Possible factors causing this difference are:
 - Different drying environment, as PC-BB1 was stored in a room at 21°C with an average relative humidity of 35%, while PC-BB2 was stored in a humidity chamber at 23°C and 50% humidity changing to 25°C after 7days to increase the evaporation rate. For PC-BB2 the initial measurement was also taken after 10days of wet curing instead of 7days

⁴ Nilsen, U. & Aitcin, P. C. 1992

- The measuring instrument is sensitive and can easily be unbalanced causing incorrect reading. Problems were experienced with the apparatus while prisms PC-BB2 were measured
- The lightweight concrete prisms cast from PC-BB2 have higher proportions of paste than prisms PC-BB1, which were slightly lacking paste

The shrinkage in the structural concrete is similar to the shrinkage experienced in conventional concrete, which in New Zealand shrinks between 650 and 1100 *microstrains* in 56 *days* depending on the type of aggregate used.⁵

7.1.1 Low and high shrinkage concrete strip

To estimate the effect of differential shrinkage on the amount of warping, a slender strip (1350x80x120mm) was cast containing:

- Low shrinkage concrete, Table 7.3, instead of the structural concrete in the variable density concrete
- High shrinkage concrete, Table 7.3, instead of the lightweight concrete in the variable density concrete

Table 7.3 – Mix designs for the low and high shrinkage concretes

Low shrinkage	1m ³
Portland cement	200kg
Fly ash	100kg
Water	140L
Natural sand	450kg
PAP 7	450kg
Limestone	1000kg
Shrinkage reducing admixture (sika)	5L
Super-plasticizer (sika)	1.5L
Density	2347kg/m³

High shrinkage	1m ³
Portland cement	365kg
Water	220L
Greywacke sand	1000kg
Greywacke stone [5mm]	750kg
Density	2335kg/m³

The high shrinkage concrete was supposed to have two times higher shrinkage than the low shrinkage concrete, while other hardened properties being the same. Initially it was aimed to get 40MPa concretes with less than 400 *microstrain* and more than 1000 *microstrain* shrinkage in 56 *days*.

The test results for the low and high shrinkage concretes are listed in Table 7.4. The high shrinkage concrete is slightly weaker and stiffer than the low shrinkage concrete. After 56 *days*, the high shrinkage concrete is shrinking 1.8 times more than the low shrinkage concrete. The slight difference in hardened properties should not have significant effect on the test result, as the main purpose was to check the behaviour of a member only experiencing differential shrinkage.

⁵ Mackechnie, J.R. 2006

Table 7.4 – Material properties at 28days and 56days shrinkage of low (LS) and high (HS) shrinkage concretes

MIX	Density [kg/m ³]	Strength [MPa]	Modulus of elasticity [GPa]	28days shrinkage [microstrain]	Ratio	56days shrinkage [microstrain]	Ratio
LS	2364	37.5	24.9	456	1.9	627	1.8
HS	2310	35.3	28.3	863		1128	

7.2 Warping (curling)

To measure the warping, several samples were made using various mix designs, different curing conditions and with different amount of stratification as listed in Table 7.1. All the samples had Ø4x75x75mm steel mesh in the bottom, structural layer with 20mm cover. The samples were stored standing vertically having the stratified sides sealed, trying to simulate a wall panel as shown in Figure 7.3.

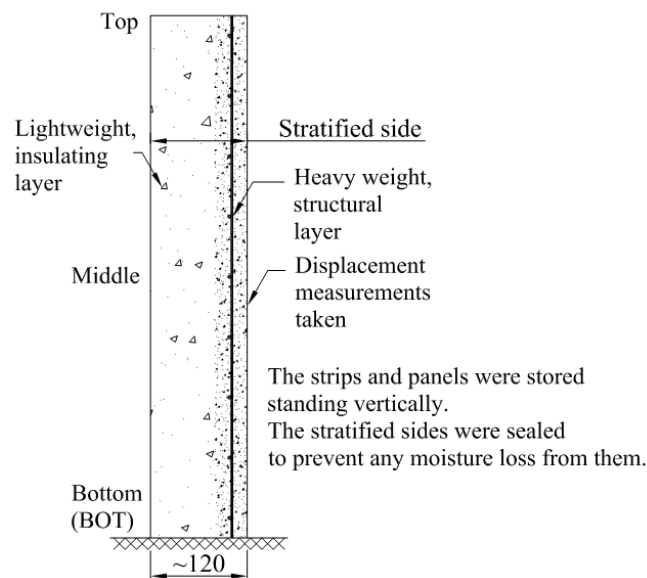


Figure 7.3 – Storing of the variable density samples to be measured for warping

The amount of warping was measured in three ways:

- By simulating the SPS plate test on strips, this method was not found successful
- By placing strain gauges on the exposed panels and some strips to measure the strain difference. This was not found successful
- By placing a straight edge on the structural side of the panels and measure the deflection by using feeler gauges. This method was found to give a good indication of the amount of warping

As the deflection is measured by having the structural side of the beams and panels facing up, the samples are described as concave and convex according to that as shown on Figure 7.4.

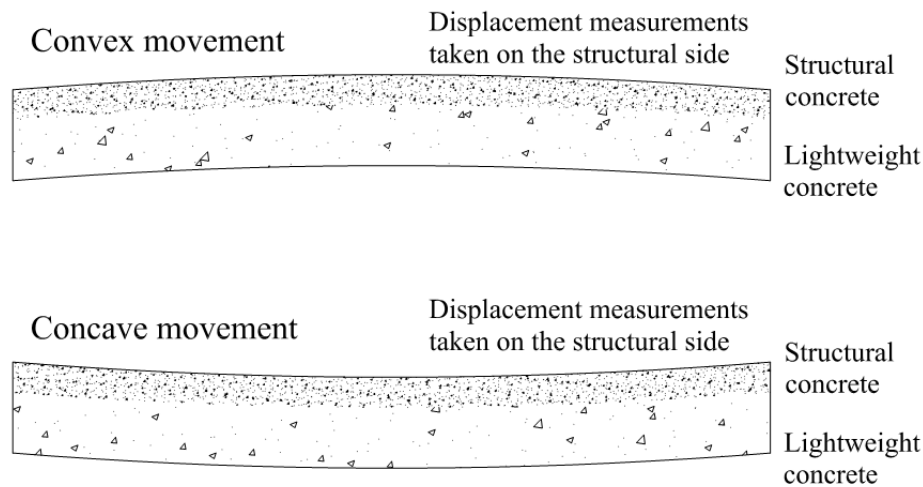


Figure 7.4 – Convex and concave movement of panels and beams being measured for warping

To provide sufficient serviceability, it is a common guideline to except a deflection that is less than:

$$\frac{1\text{mm}}{500\text{mm}} \times 100 = 0.2\%$$

The deflection on the samples was therefore calculated by using:

$$\frac{\text{deflection} / 1000 [\text{mm}]}{\text{Length measured over}} \times 100 = \text{deflection} [\%]$$

Drawings of all the samples where the deflections were measured and the deflection measurements are displayed in the appendix.

7.2.1 Panels

All the panels cast were 1000x700x~120mm but contained different aggregate and binder materials. The inorganic polymer cement (IPC) concrete panels were all cast by Mackechnie at the University of Canterbury⁶ but tested and measured at the same time as the Portland cement (PC) panels by Sævarsdóttir. To calculate the difference in deflection, the following lengths were used for the panels:

- Short side – 700mm
- Long side – 1000mm
- Diagonal line – 1221mm

Drawings of all the panels as well as the deflection measurements are displayed in the appendix.

7.2.1.1 Outdoor exposed panels

The outdoor exposed panels (PC-GB, PC-PUM, IPC-GB & IPC-PUM1) listed in Table 7.1 were left outside during the summer to autumn in Christchurch weather, that is, from December 2006 till May 2007. An attempt was made to place strain gauges on the lightweight and structural

⁶ Mackechnie, J.R. 2007

faces to measure the strain difference with time. This method did not give consistent results and was therefore not developed any further. The panels were therefore measured by placing a straight edge on the structural side and the deflection measured by the use of feeler gauges.

Initially, the panels showed almost no sign of deflection or warping, as the deflection varied between 100 and 150 *micrometers*. After 5 months of exposure, the deflection had significantly increased as listed in Table 7.5.

Table 7.5 – Deflection of outdoor exposed panels

Panel	Deflection short side [micrometers and %]		Deflection long side [micrometers and %]		Deflection diagonal line [micrometers and %]	
PC-GB	430	0.061%	1350	0.135%	900	0.074%
PC-PUM	800	0.114%	720	0.072%	1200	0.098%
IPC-GB	800	0.114%	750	0.075%	720	0.059%
IPC-PUM1	660	0.094%	1300	0.130%	850	0.070%

The PC-GB panel seemed to be twisting as well as warping, as the panel is concave at the top but convex at the bottom. This panel is also concave on the long side having the deflection increasing from 400 to 1350 *micrometers* from one edge to the other. The panel is also concave in both directions on the diagonal line.

The deflection readings of the IPC panels can also be affected by their bad finish. When measuring the deflection by using the feeler gauges the paste can get a bit scraped off, increasing the measured deflection.

The panels are in general showing convex warping as expected by the material properties of the layers, despite PC-GB being concave. There are some indications that the panels are twisting slightly as there are some measurements showing either concave or double convex warping. When comparing the maximum deflection in the panels listed in Table 7.5, there does not seem to be any trend:

- The maximum deflection is not always on the short or the long side
- The deflection does not seem to increase or decrease depending on the materials or binder used
- The deflection does not seem to increase or decrease by the amount of stratification as the Portland cement panels were poorly stratified whereas the inorganic polymer cement ones were really well stratified, almost being over stratified. The aggregate or the binder materials are not the same within the panels

All these deflections are less than 0.2%, and should therefore not significantly affect the serviceability of the panel.

7.2.1.2 Panels kept at 35°C temperature and 27% humidity

Four panels, PC-BB15, PC-BB45, IPC-BB and IPC-PUM2, were cast using three different mix designs, two of the panels were cast using the same mix design but with different vibration times. This allowed for panels having different strength but the PC-BB15 & 45 panels had almost the same stratification coefficient despite different vibration times applied. The effect of different

stratification could therefore not be tested on these panels. The panels were measured by placing a straight edge on the structural side and the deflection measured by the use of feeler gauges.



Figure 7.5 - Panels dried in a controlled environment at 35°C temperature and 27% humidity for 80days

The panels were kept in a temperature and humidity controlled environment at 35°C and 27% humidity. They were measured in the beginning, after 42days and after 80days in the drying environment. The initial measurements were significantly higher for these panels than for the outdoor exposed ones, indicating that the timber moulds used might have deformed slightly when used prior to casting the outdoor exposed panels. The deflection is taken as the difference between the initial measurement and the deflection at 42 and 80days.

Table 7.6 - Maximum difference in deflection after 80days of drying

Panel	Deflection short side [micrometers and %]		Deflection long side [micrometers and %]		Deflection diagonal line [micrometers and %]	
PC-BB15	750	0.107%	900	0.090%	800	0.066%
PC-BB45	600	0.086%	750	0.075%	950	0.078%
IPC-BB	900	0.129%	1600	0.160%	1950	0.160%
IPC-PUM2	1300	0.186%	510	0.051%	1100	0.090%

The measurement taken on panels IPC-BB and IPC-PUM2 are not as accurate as the measurements taken on PC-BB15 and PC-BB45, as the IPC mixes had too high water proportion, leaving them with a bad finish. The paste layer tended to scrape off as the deflection was measured by using the feeler gauges. The IPC panels used in this testing were not ideal having both excessive water and inadequate activators resulting in higher drying shrinkage. All the deflections were less than 0.2%. The serviceability of the variable density panel should therefore not be affected by its amount of warping.

The panels are in general showing convex warping as expected by the material properties of the layers:

- PC-BB15 is bending in a convex shape everywhere except for one of the diagonal lines that almost remained the same, having a slight concave warping decreasing with time

- PC-BB45 is bending in a convex shape having the line in the middle on the long side slightly double convex
- IPC-BB is bending in a convex shape. Although measurements for this panel might not be as accurate as for the other panels as it was laid up against a wall when being measured due to lack of space (Figure 7.5)
- The IPC-PUM2 panel is bending in a convex shape having the middle line on the long edge and the diagonal lines slightly double convex. The double convex shape is decreasing

When comparing the maximum deflection in the panels as listed in Table 7.6 and viewed on figures in the appendix, there are certain trends observed:

- IPC-PUM2 experienced larger amount of warping than the other panels
- PC-BB45 in general experiences less warping and twisting than PC-BB15
- The maximum deflection is generally found to be on the short side
- The deflection seems to be higher for the IPC panels than the PC ones
- The amount of increase in warping decreases with time

There are two possible reasons for the IPC-PUM2 panel to warp more; higher readings due to bad finishing as well as the fact that the mix contained too much water causing it to be so weak that it tended to break as it was being handled. The other reason can be related to higher strength in the lightweight concrete, as it contains pumice instead of 2-4mm expanded glass beads. As the strength of the lightweight concrete is closer to the strength of the structural layer, the concrete is more prone to warp as the lightweight concrete provides more resistance to creep when following the structural concrete.

The PC-BB45 panel generally has less warping as well as more even difference in deflection over the panel than PC-BB15. At first this was related to better stratification of PC-BB45 than PC-BB15 as it was vibrated for a longer time, but after finding the stratification coefficient being almost the same, better stratification might not be the reason. As both samples are very well stratified this could though still be the reason, as the concrete starts losing paste when over vibrated, and might not be picked up by the stratification coefficient. As the concrete has better stratification, less restraint is provided by the lightweight concrete to creep. This is therefore the same behaviour as experienced by the higher deflection of IPC-PUM2.

The fact that the IPC panels had higher deflections than the PC ones are most likely related to the bad finish, as the paste layer tended to scrape off as the deflection was being measured.

The difference between the initial deflection measurements and the 42days deflection measurements is higher than the difference between the 42days measurements and the 80days ones. As the concrete dries out, the increase in warping decreases.

As mentioned before, all these deflections are less than 0.2% and should therefore not affect the serviceability of the panel.

7.2.1.3 Comparison of different curing environments

The change in deflection of all the panels measured are listed in Table 7.7 and displayed on Figure 7.6.

Table 7.7 - Maximum difference in deflection on the measured panels

Panel	Drying	Deflection short side	Deflection long side	Deflection diagonal line
PC-GB	Outdoor exposure for 5 months	0.061%	0.135%	0.074%
PC-PUM		0.114%	0.072%	0.098%
IPC-GB		0.114%	0.075%	0.059%
IPC-PUM1		0.094%	0.130%	0.070%
PC-BB15	Kept at 35°C temperature and 35% humidity for 80days	0.107%	0.090%	0.066%
PC-BB45		0.086%	0.075%	0.078%
IPC-BB		0.129%	0.160%	0.160%
IPC-PUM2		0.186%	0.051%	0.090%

As mentioned before, the serviceability of the panels should not be affected as all these deflections are less than 0.2%. The general trend observed for all the panels is that they tend to warp into a convex shape with some of them twisting slightly.

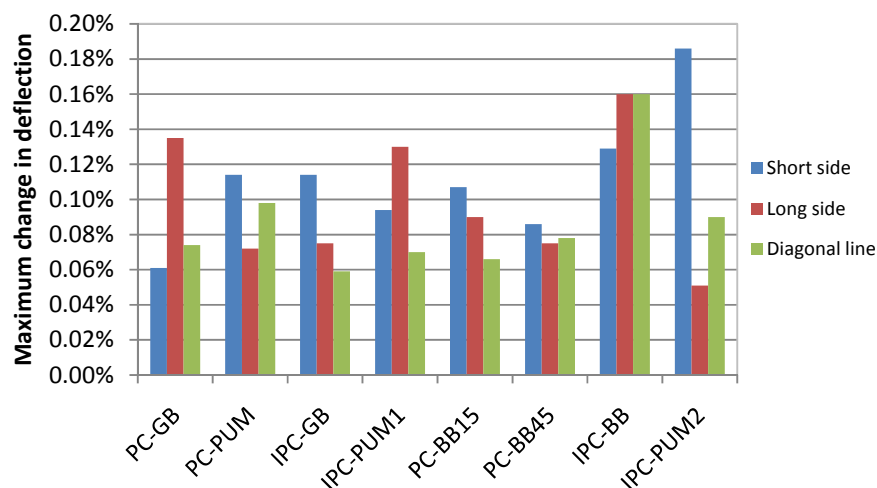


Figure 7.6 - Maximum change in deflection of the panels

When comparing all the deflection measurements for all of the eight panels, cured in different environments, certain facts must be considered:

- The panels kept at 35°C were measured after 80days of drying, whereas the outdoor ones were measured after 5months
- The PC based outdoor exposed panels were not well stratified, while the IPC ones were over vibrated. The panels kept at 35°C had good stratification
- The panels are cast using different materials and mix designs

The following trends were observed between the panels dried in the two different environments:

- The IPC based panels experience more deflection when dried at 35°C than when outdoor exposed
- Similar difference in deflection was found between the PC panels kept at 35°C and the outdoor exposed ones

As the panels dry out faster when kept at 35°C, more warping should occur in comparable panels. The fact that the inorganic polymer panels kept at 35°C deflect more than the outdoor exposed ones is most likely due to faster drying but can also be related to poor finish. The fact that the Portland cement panels kept at 35°C are giving similar deflection measurements as the outdoor exposed ones, could be related to shorter measuring time and better stratification which reduces the amount of warping.

7.2.2 Strips

The strips measured for warping can be divided into three groups:

- Strips where the strain difference was measured with time and the SPS plate method was used
- Strips gained from cutting panels
- Slender strips

The strips gained from the panels as well as the slender strips were measured by placing a straight edge on the structural side and the deflection measured by using feeler gauges. The deflection was usually measured on the top, bottom and if appropriate in the middle as is displayed in Figure 7.3. Drawings of all the strips as well as the measured deflection on them are displayed in the appendix.

7.2.2.1 Strain gauges and SPS plate method

Five strips, PC-GB1 & 2 and PC-PUM1, 2 & 3, were cast using two mixes and the amount of warping measured, by using a modified version of the SPS plate method⁷ and by measuring the change in strain with time on one of the stratified sides. Neither of these test methods was found to be successful.

The SPS plate method was tried; one end of the strips was clamped down or restrained on a straight surface table and the amount of upward movement on the other end measured using feeler gauges (Figure 7.7). This method was not found feasible as the lightweight material got crushed and the amount of restraint was inconsistent. This changed the amount of upward movement.

⁷ McDonald, J.E.; Vaysburd, A.M. & Poston, R.W. 2000:1-12



Figure 7.7 – Configuration used to measure upward movement and strain differences of stratified beams

The strain gages were placed, both vertically and horizontally to measure the strain change with time as can be seen on Figure 7.7. The change in strain over time was not significant but the reading results are listed in Table 7.8 and Table 7.9.

The strain (ε) can be calculated by dividing the change in length (δl) by the initial length (l_0), here being $100mm$.

$$\varepsilon = \frac{\delta l}{l_0}$$

No obvious trend was found between these strain results. The strain is always a bit higher in the lightweight layer than in the structural layer except for PC-PUM3. But the difference varies and is not significant in some cases. The strips might not be slender enough to experience a significant strain difference over such a short period of time, but no correlation was found between the measurements to make this method feasible.

As later confirmed by other warping tests, the likely explanation for the small difference in strain is that the variable density concrete is not experiencing significant amount of warping. That is, the weaker lightweight concrete is creeping as the heavy structural concrete shrinks. The lightweight concrete cracks and deforms to follow the structural concrete.

Table 7.8 – Measured change in length with time and calculated strains for PC-GB mixes

PC-GB1 [120x120x470mm]						
<i>Points</i>	<i>7days</i>	<i>68days</i>	<i>99days</i>	<i>Є [99days]</i>	<i>229days</i>	<i>Є [229days]</i>
AC	-92	-86	-108	-1.08	-128	-1.28
AB	12	-79	-104	-1.04	-109	-1.09
CD	6	-77	-107	-1.07	-126	-1.26
BD	0	-35	-33	-0.33	-13	-0.13
EG	6	-100	-142	-1.42	-178	-1.78
EF	-3	-88	-110	-1.10	-124	-1.24
GH	-7	-31	-40	-0.40	-43	-0.43
FH	-29	-44	-54	-0.54	-31	-0.31
PC-GB2 [150x120x530mm]						
<i>Points</i>	<i>7days</i>	<i>68days</i>	<i>99days</i>	<i>Є [99days]</i>	<i>229days</i>	<i>Є [229days]</i>
AB	-11	64	34	0.34	-81	-0.81
BD	-23	-111	-144	-1.44	-193	-1.93
AC	-28	-123	-155	-1.55	-178	-1.78
CD	-6	-50	-49	-0.49	-40	-0.40
EF	-9	-54	-94	-0.94	-165	-1.65
EG	-48	-150	-188	-1.88	-218	-2.18
FH	-14	-100	-130	-1.30	-189	-1.89
GH	-14	-58	-55	-0.55	-80	-0.80

Table 7.9 – Measured change in length with time and calculated strains for PC-PUM mixes

PC-PUM1 [120x120x470mm]						
Days	7days	68days	99days	€ [99days]	229days	€ [229days]
AC	-20	-129	-146	-1.46	-188	-1.88
AB	-17	-85	-98	-0.98	-129	-1.29
CD	-6	-78	-95	-0.95	-132	-1.32
BD	-21	-42	-42	-0.42	-66	-0.66
EG	-25	-124	-140	-1.40	-182	-1.82
EF	-14	-84	-92	-0.92	-120	-1.20
GH	-15	-110	-120	-1.20	-154	-1.54
FH	-38	-30	-43	-0.43	-43	-0.43
PC-PUM2 [120x120x470mm]						
Days	7days	68days	99days	€ [99days]	229days	€ [229days]
AB	-24	-35	-155	-1.55	-187	-1.87
BD	-16	-35	-112	-1.12	-253	-2.53
AC	-16	-54	-98	-0.98	-12	-0.12
CD	-23	-14	-24	-0.24	-44	-0.44
EF	-35	-120	-144	-1.44	-184	-1.84
EG	-21	-68	-84	-0.84	-116	-1.16
FH	-23	-66	-81	-0.81	-103	-1.03
GH	-27	-21	-25	-0.25	-35	-0.35
PC-PUM3 [150x150x530mm]						
Days	7days	68days	99days	€ [99days]	229days	€ [229days]
AC	-20	23	29	0.29	24	0.24
AB	-18	-32	-45	-0.45	-58	-0.58
CD	-75	-98	-111	-1.11	-132	-1.32
BD	-35	-75	-78	-0.78	-90	-0.90
EG	-90	-48	-57	-0.57	-99	-0.99
EF	-53	-93	-103	-1.03	-125	-1.25
GH	-50	-101	-117	-1.17	-125	-1.25
FH	-75	-112	-94	-0.94	-114	-1.14

7.2.2.2 Panel strips

Three strips approximately 650x150x120mm, were produced by cutting 1000x700x~120mm panels that had been wet cured for 7days at 21°C. After cutting the strips, they were stored at 21°C and 50% humidity, changing to 35% after a month. The panels were cast using the same

mix design but had different amount of stratification to estimate the effect stratification had on warping:

- PC-GB15 vibrated for 15seconds with a stratification coefficient of 18.2%
- PC-GB30 vibrated for 30seconds with a stratification coefficient of 24.6%
- PC-GB45 vibrated for 45seconds with a stratification coefficient of 27.9%

The amount of warping was estimated by measuring the deflection difference with time, using a straight edge and feeler gauges. The amount of deflection was measured initially and after 21, 49 and 151days, on three lines over the length of the strips as can be seen on Figure 7.8. As there were some variations in the initial deflection, due to variations within the moulds, the deflection was analyzed using the difference between the initial deflection and the deflection measured after 21, 49 and 151days. All the strips experienced convex warping, as expected by the material properties of the variable density concrete.



Figure 7.8 – The strips after 151days of drying

The length that the deflection is measured over is 650mm. The deflection is therefore calculated by using:

$$\frac{\text{deflection} / 1000 [\text{mm}]}{650 \text{ mm}} \times 100 = \text{deflection} [\%]$$

The change in deflection never exceeded 0.2%, and should therefore not significantly affect the serviceability of the variable density concrete. The maximum change in deflection over the three lines is displaced on Figure 7.9, whereas the average change in deflection is plotted on Figure 7.10.

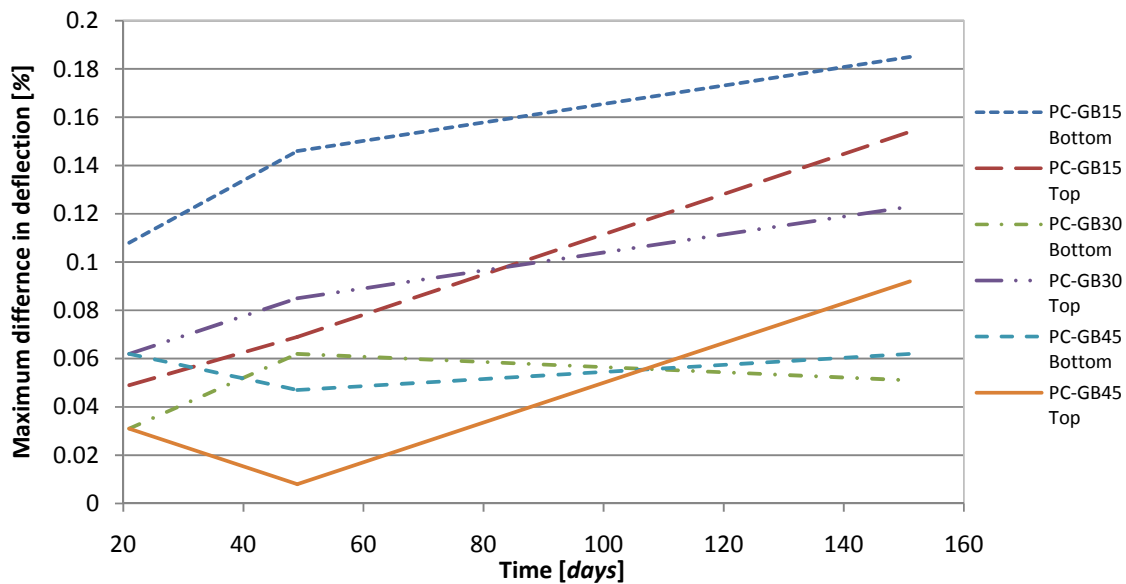


Figure 7.9 – Maximum difference in deflection on the three lines

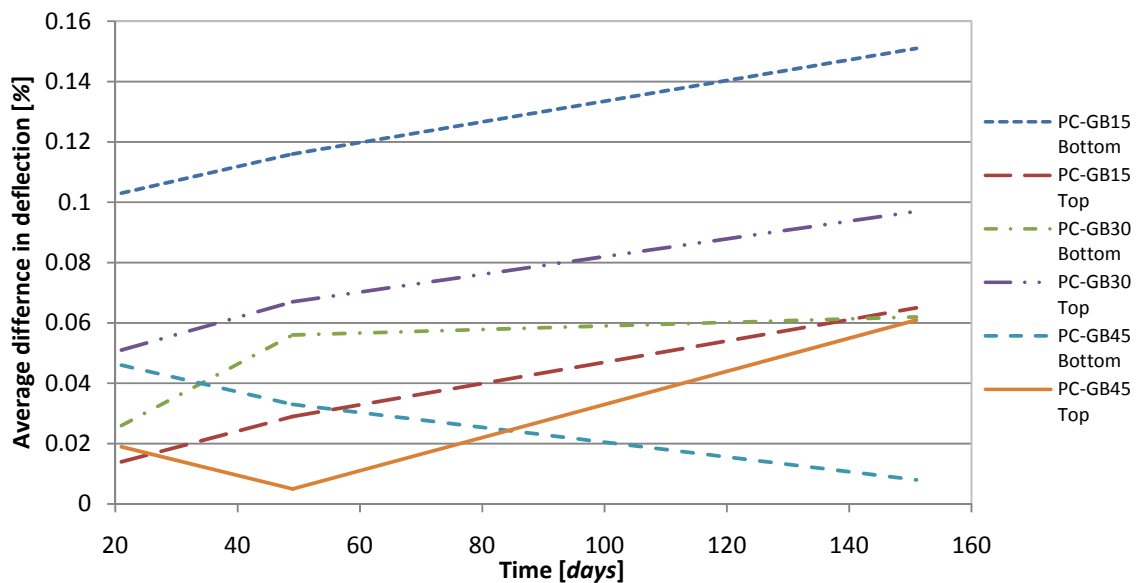


Figure 7.10 – Average difference in deflection

After 49days of drying, the strips are already behaving differently depending on their amount of stratification, as the maximum and average deflection is increasing on PC-GB15 and PC-GB30 but decreasing on PC-GB45.

After 151days the average deflection is only decreasing at the bottom of PC-GB45 but at the top, the deflection has increased significantly becoming higher than the deflection at the bottom. The maximum difference in deflection on the other hand increases slightly at the bottom of PC-GB45 indicating slight twisting within the strip. On the bottom of PC-GB30, the opposite is happening as the maximum deflection is decreasing slightly while the average deflection increases slightly. The deflection on PC-GB15 remains higher at the bottom. The same trend is observed after 49days, as better stratified strips show smaller amount of warping.

With better stratification the change in deflection decreases due to more stress and strain release in the lightweight concrete when it is not contaminated with stronger particles. The lightweight concrete is so much weaker than the structural concrete that it creeps to follow the deformation of the structural concrete.

7.2.2.3 Slender strips

Four slender (1350x80x120mm) strips were cast to confirm the affect of stratification on the amount of warping and to prove that the lightweight concrete was creeping to follow the stronger structural concrete. Three strips were cast using the same mix design and the fourth strip had low- and high shrinkage concrete. The strips cast were:

- PC-BB15S vibrated for 15seconds having the lowest degree of stratification
- PC-BB30S vibrated for 30seconds having moderate degree of stratification
- PC-BB45S vibrated for 45seconds having the highest degree of stratification
- LS-HS having low shrinkage concrete instead of the structural concrete, and high shrinkage concrete instead of the lightweight concrete. Other hardened properties of these concretes were similar to estimate the amount of warping caused by differential shrinkage

These strips were wet cured for 7days at 21°C and then kept at 35°C temperature and 27% humidity for 60days. The amount of warping was estimated by measuring the deflection difference with time, using a straight edge and feeler gauges. The amount of deflection was measured initially and after 7, 13, 23, 35, 49 and 60days of drying on the PC-BB strips and after 7, 20, 27, 34, 45 and 65days on the LS-HS strip.



Figure 7.11 – The slender strips after 49 and 45days of drying

All the strips cracked while being tested which must be taken into account when analyzing the results, some of the cracks seemed to be related to internal stresses within the strips whereas other cracks or failures seemed to be caused by handling:

- Strip GB-BB15S cracked close to the top after 23days of drying and in the middle after 60days of drying. The top crack seemed to be due to internal stresses whereas the middle crack seemed to have failed due to handling
- Strip GB-BB30S cracked in the middle after 49days of drying due to internal stresses
- Strip GB-BB45S cracked in the middle after 49days of drying due to handling

The length that is measured over is 1350mm; the deflection is therefore calculated by using:

$$\frac{\text{deflection}/_{1000} [\text{mm}]}{1350 \text{ mm}} \times 100 = \text{deflection} [\%]$$

The change in deflection between the initial measurement and the measurements taken over a period of 60 and 65 days never exceed 0.2%. The amount of warping should therefore not significantly affect the serviceability of the variable density concrete.

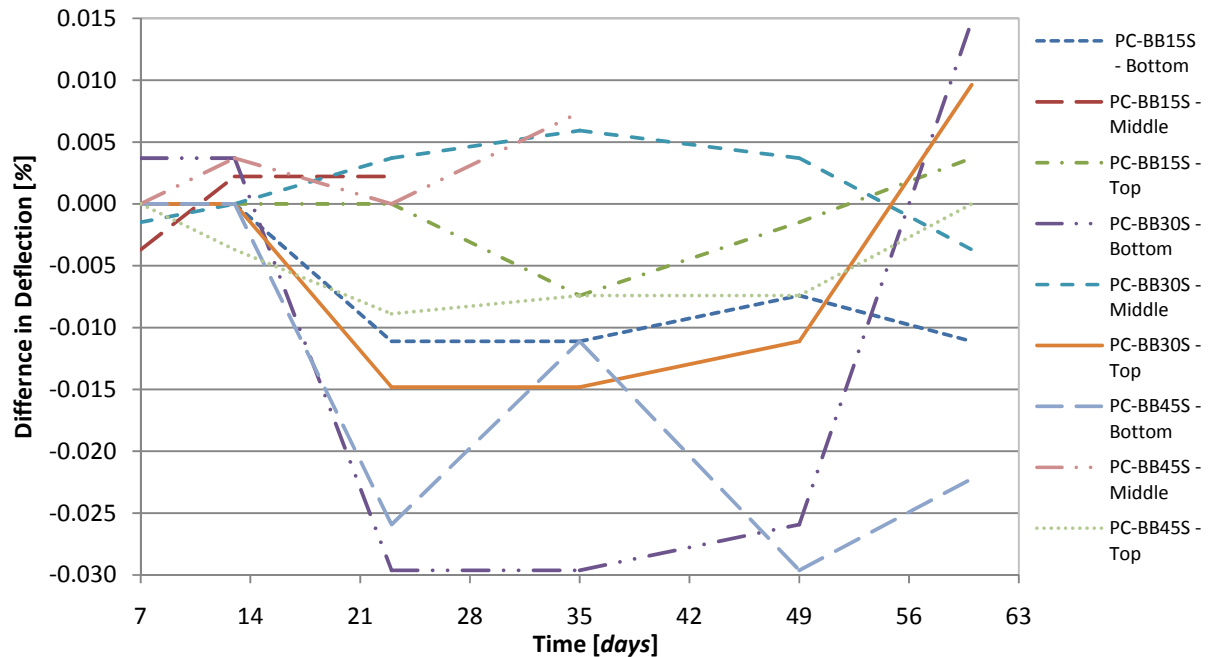


Figure 7.12 - Difference in deflection on PC-BB15S, 30S & 45S

The deflection difference displayed in Figure 7.12 is fluctuating at approximately zero. PC-BB15S cracks first due to stresses within the concrete and 2 weeks later strip PC-BB30S has cracked. Strip PC-BB45S did not crack due to internal stresses but cracked due to handling. This indicates more stress and strain release in the lightweight material section when not interfered with stronger particles, as PC-BB15S had the worst stratification while PC-BB45S had the best stratification. After strip PC-2BB15S and 45S cracked due to handling the middle line measurements are not displayed on Figure 7.12.

These are several factors that can control the lower deflection in the slender strips than in the panel strips such as:

- Different fine grade lightweight material used, experiencing less shrinkage
- More slender than other strips cast before
- Dried faster; that is, at higher temperature and lower humidity
- Measured over a shorter period

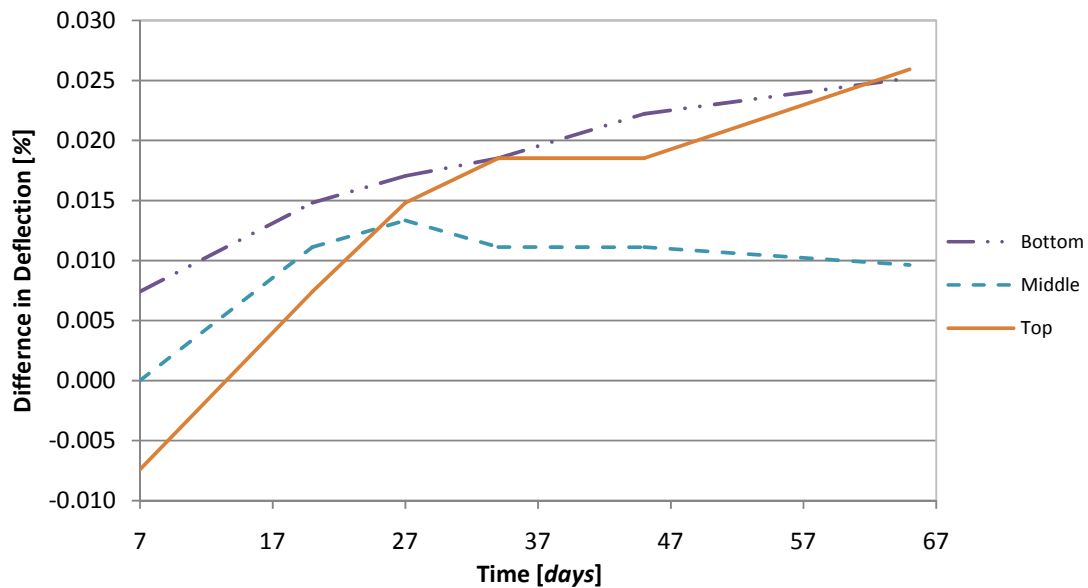


Figure 7.13 - Difference in deflection for strips LS-HS

The convex warping shape of the LS-HS strip increased constantly with time as the deflection increases at the top and the bottom but decreased in the middle, as can be seen in Figure 7.13. The increase in warping is therefore only related to the differential shrinkage as other hardened properties of the low and high shrinkage concretes are the same.

The gradual increase in strain with time under load or the increase in strain under sustained stress in conventional concrete is due to creep. But creep can also be in the form of relaxation, if a stressed concrete specimen is subjected to a constant strain, creep will manifest itself as a progressive decrease in stress with time.⁸ As the lightweight insulating layer is significantly weaker and more elastic, it follows the deformations of the structural layer, and the only way it can do that is by creeping.

It was found that IPC-PUM2 warped more than the other panels stored at 35°C as well as the LS-HS (low and high shrinkage strip) warped increasingly while other variable density strips of the same size and cured under the same conditions showed around notch deflection. This indicates that as the strength of the lightweight concrete is closer to the strength of the structural concrete, the concrete is more prone to warp as the lightweight concrete provides more resistance to creep and does not follow the deformation of the structural concrete as easily.

7.3 Drying shrinkage and warping

As differential shrinkage is the main factor causing warping within a member, different drying shrinkage for various mixes was compared to the amount of warping experienced from the same mix design.

The lower shrinkage of the inorganic polymer cement (IPC) concretes did not result in decreased amount of warping on the panels when compared to the Portland cement (PC) ones. The deflection measurements for the IPC concretes were not as reliable as for the PC ones due to bad

⁸ Neville, A.M. 1995:449

finishing of the IPC concrete, as the paste got scraped off while being measured using feeler gauges. Here, it must also be noticed that the IPC panel mixes had some excess water and inadequate activates increasing the drying shrinkage.

There are several factors that can control the lower deflection in the PC-BB15S, 30S and 45S than in the PC-GB15, 30 and 45, but one of these factors was the amount of shrinkage. The PC-BB strips are cast using fine graded expanded glass beads as fine aggregate instead of perlite in the PC-GB strips. The PC-GB1 & 2 shrinkage prisms containing perlite have significantly higher drying shrinkage than the PC-BB prisms. The ratio between the shrinkage in the lightweight and the structural concretes is about the same for both mixes.

The trend is that, as the drying shrinkage increases the amount of warping increases.

7.4 Conclusion

Drying shrinkage of the lightweight concrete was typically twice of that measured in the structural concrete. The shrinkage depended on the materials and mix design being used:

- Inorganic polymer concretes had lower drying shrinkage than Portland cement concretes, but the difference in shrinkage was of the same order
- Higher water binder ratios increased drying shrinkage
- Larger aggregate particles increased shrinkage in the lightweight concrete but decreased it in the structural concrete.
- Using fine graded expanded glass beads instead of perlite decreased the drying shrinkages

Convex warping (Figure 7.4) was generally experienced as expected from the material properties of the variable density concrete, but some samples twisted slightly. The amount of warping was found to be highly related to:

The amount of stratification – the amount of warping decreased with better stratification as more stress and strain relief occurred in the lightweight concrete when not interfered with stronger particles. The lightweight concrete is significantly weaker and less stiff than the structural concrete that it creeps to follow the structural concrete layer.

Drying rate – the faster the concrete is dried out, the higher amount of warping was experienced

Drying shrinkage – as the drying shrinkage decreases, the amount of warping decreases

Measuring time – longer measuring time gave a higher amount of warping. The increase in warping decreased with time

To provide sufficient serviceability, it is a common guideline to except a deflection if it is less than 1/500 or 0.2%. The amount of warping due to differential shrinkage within the variable density concrete is not as extensive as first thought, as all the deflections are less than 0.2%. Warping should therefore not significantly affect the serviceability of the panels.

7.5 References

- Australian Standard. 1992. *AS 1012.13-1992, Methods of testing concrete. Method 13: Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory*. Standards Australia.
- Mackechnie, James R. 2006. "Shrinkage of Concrete Containing Greywacke Sandstone Aggregate" *ACI Materials Journal* 103:390-396.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007. "Stratified Precast Concrete Panels for Buildings." *Concrete Plant International*, July 2007.
- Mailvaganam, N.; Springfield, J.; Repetto, W. & Taylor, D. 2000. *Curling of Concrete Slabs on Grade*. Construction Technology Update No. 44. National Research Council Canada. Web site: http://irc.nrc-cnrc.gc.ca/pubs/ctus/44_e.html.
- McDonald, James E.; Vaysburd, Alexander M. & Poston, Randall W. 2000. *Performance Criteria for Dimensionally Compatible Repair Materials*. High-Performance Materials and Systems Research Program, Information Bulletin.
- Neville, A.M. 1995. "*Properties of Concrete*" Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- Nilsen, Ulrik; Aïtcin, Pierre-Claude. 1992. "*Properties of High-Strength Concrete Containing Light-, Normal-, and Heavyweight Aggregate*." *ASTM Journal of Cement, Concrete, and Aggregates* 14:8-12.

7.6 Appendix

7.6.1 Shrinkage

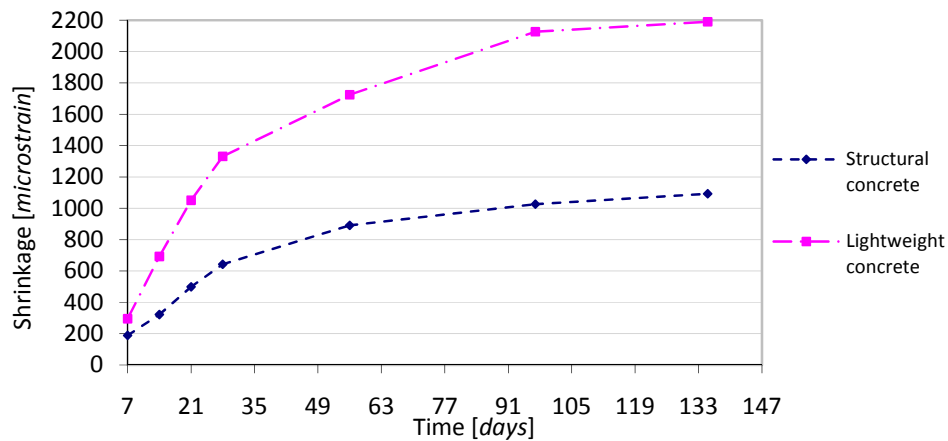


Figure 7.14 - Measured shrinkage in structural and lightweight concrete prisms gained from PC-GB1

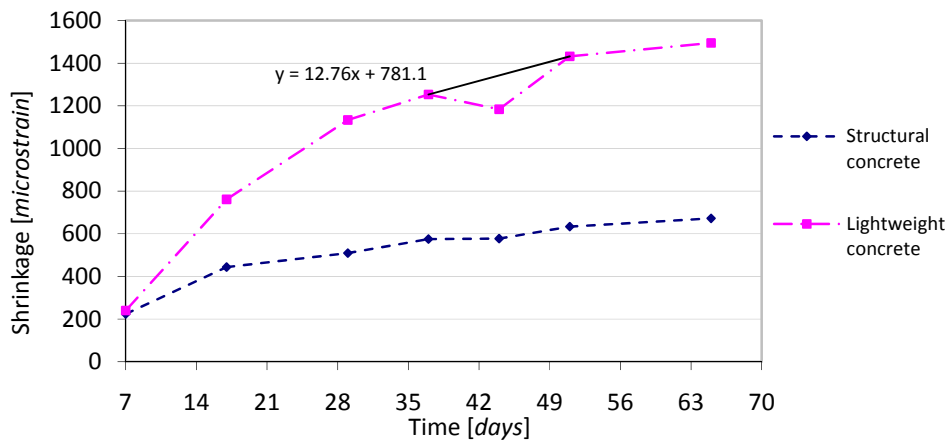


Figure 7.15 – Measured shrinkage in structural and lightweight concrete prisms gained from PC-GB2

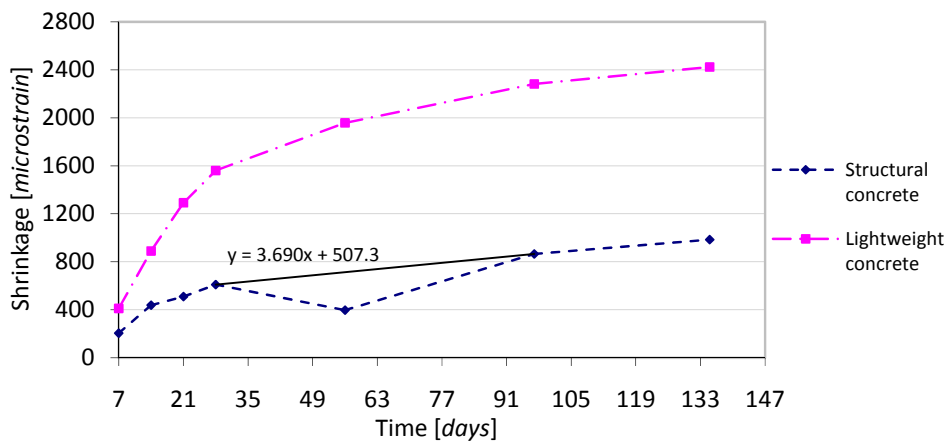


Figure 7.16 - Measured shrinkage in structural and lightweight concrete prisms gained from PC-PUM1

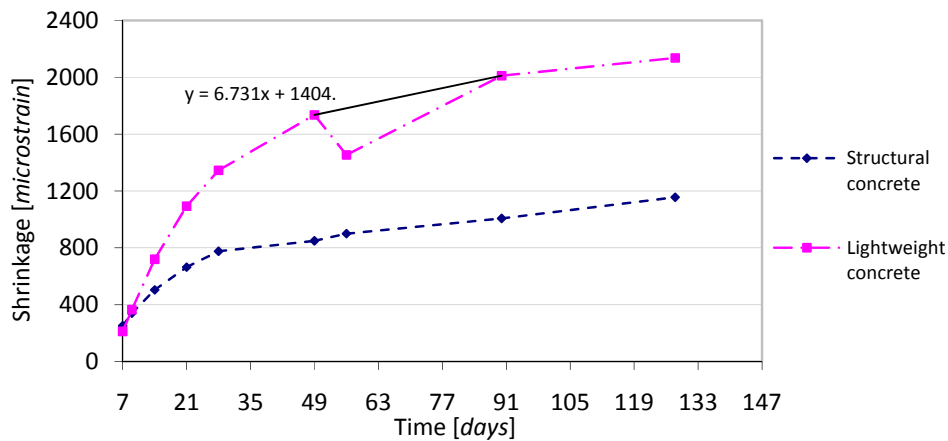


Figure 7.17 - Measured shrinkage in structural and lightweight concrete prisms gained from PC-PUM2

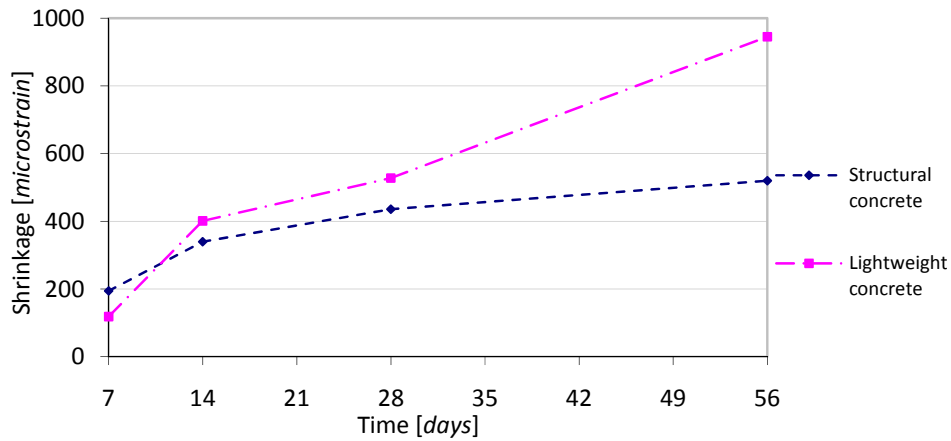


Figure 7.18 - Measured shrinkage in structural and lightweight concrete prisms gained from PC-BB1

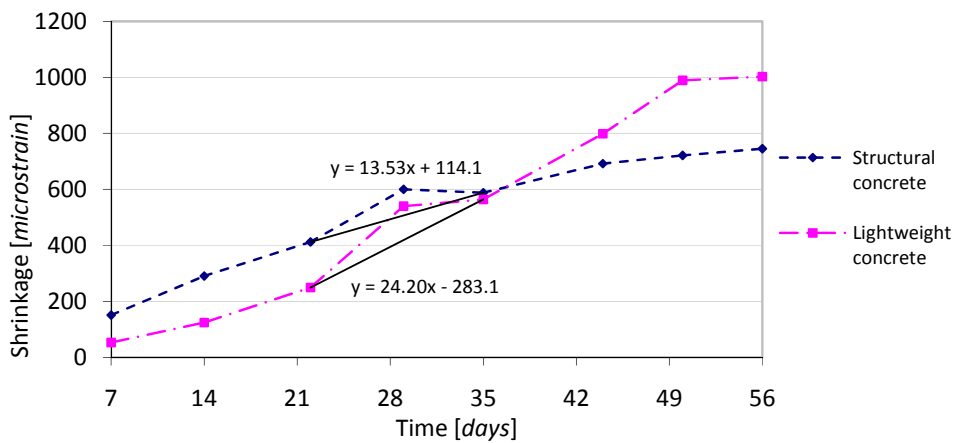


Figure 7.19 - Measured shrinkage in structural and lightweight concrete prisms gained from PC-BB2

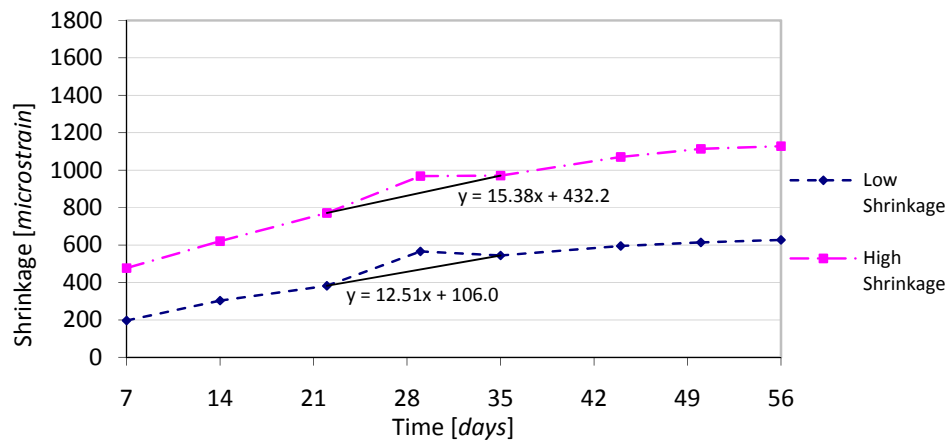


Figure 7.20 - Measured shrinkage for the high (HS) and low (LS) shrinkage concrete prisms

7.6.2 *Warping*

7.6.2.1 Panels

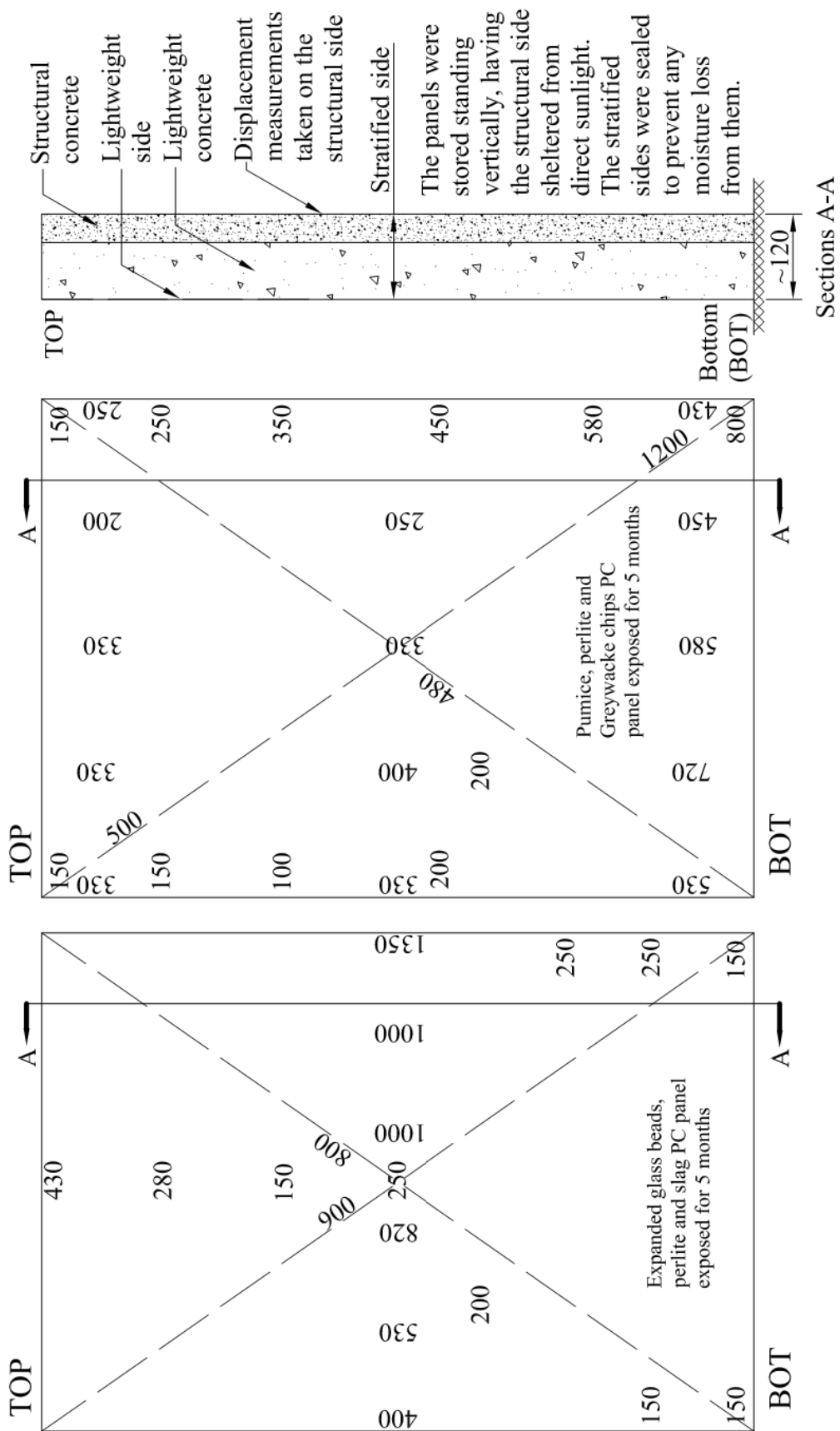


Figure 7.21 – Measured displacement on panels PC-GB & PC-PUM; exposed outdoors for 5 months

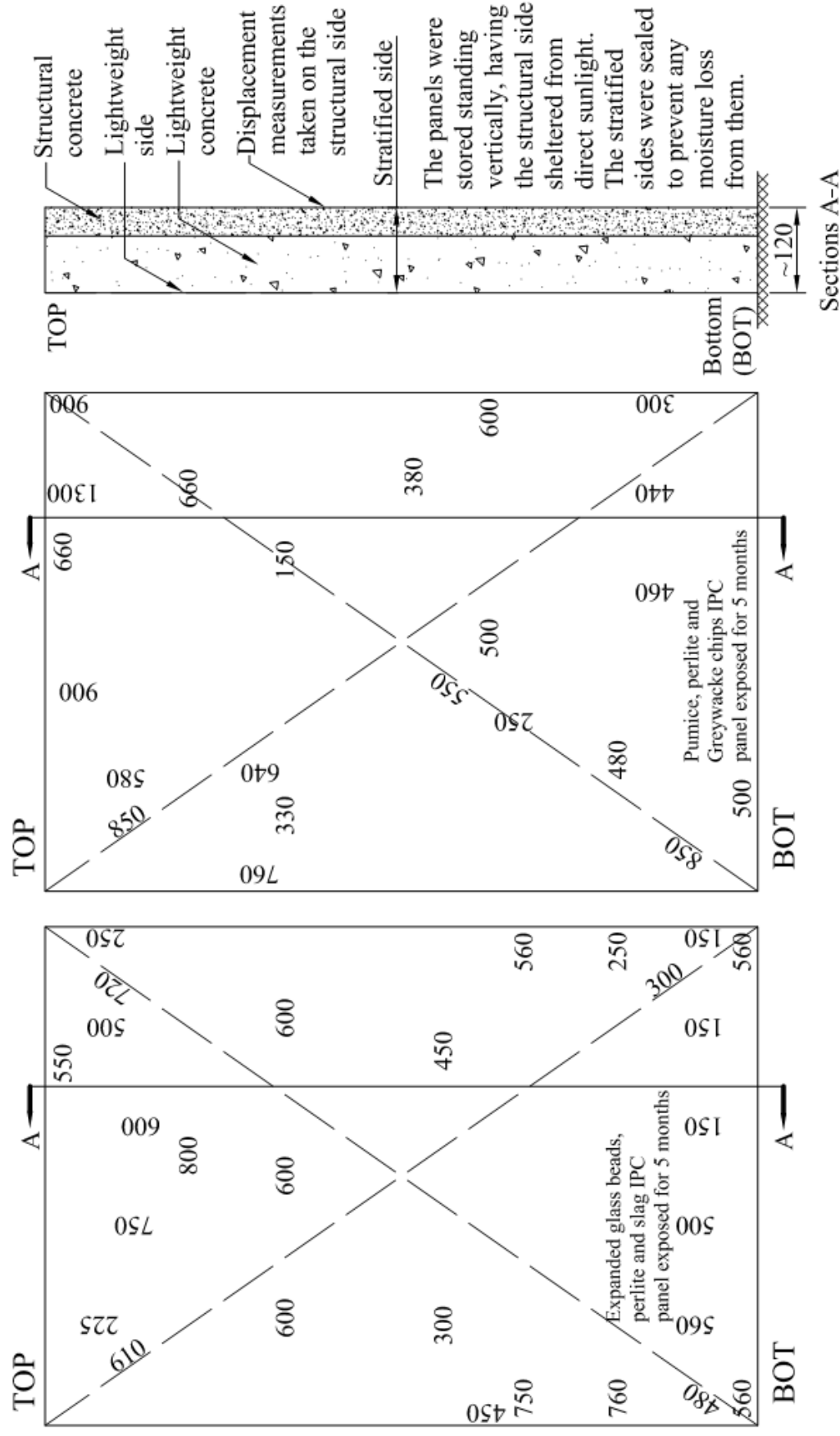


Figure 7.22 - Measured displacement on panels IPC-GB & IPC-PUM1; exposed outdoors for 5 months

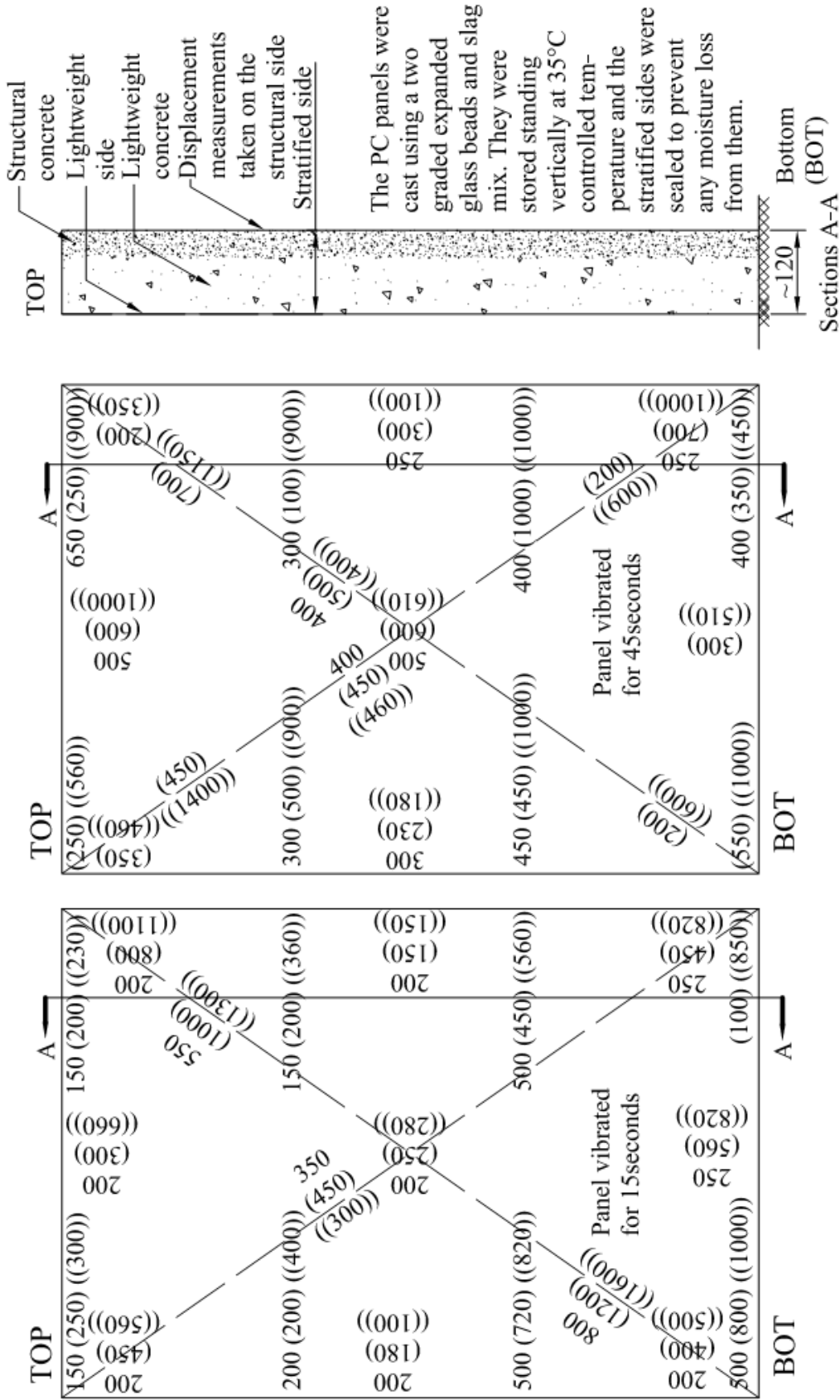


Figure 7.23 - Measured displacement on panels, PC-BB15 and PC-BB45

On Figure 7.23 the number outside the bracket is the initial measurement, the number in one bracket is the 42 days measurement and the number in the two brackets is the 80 days measurement

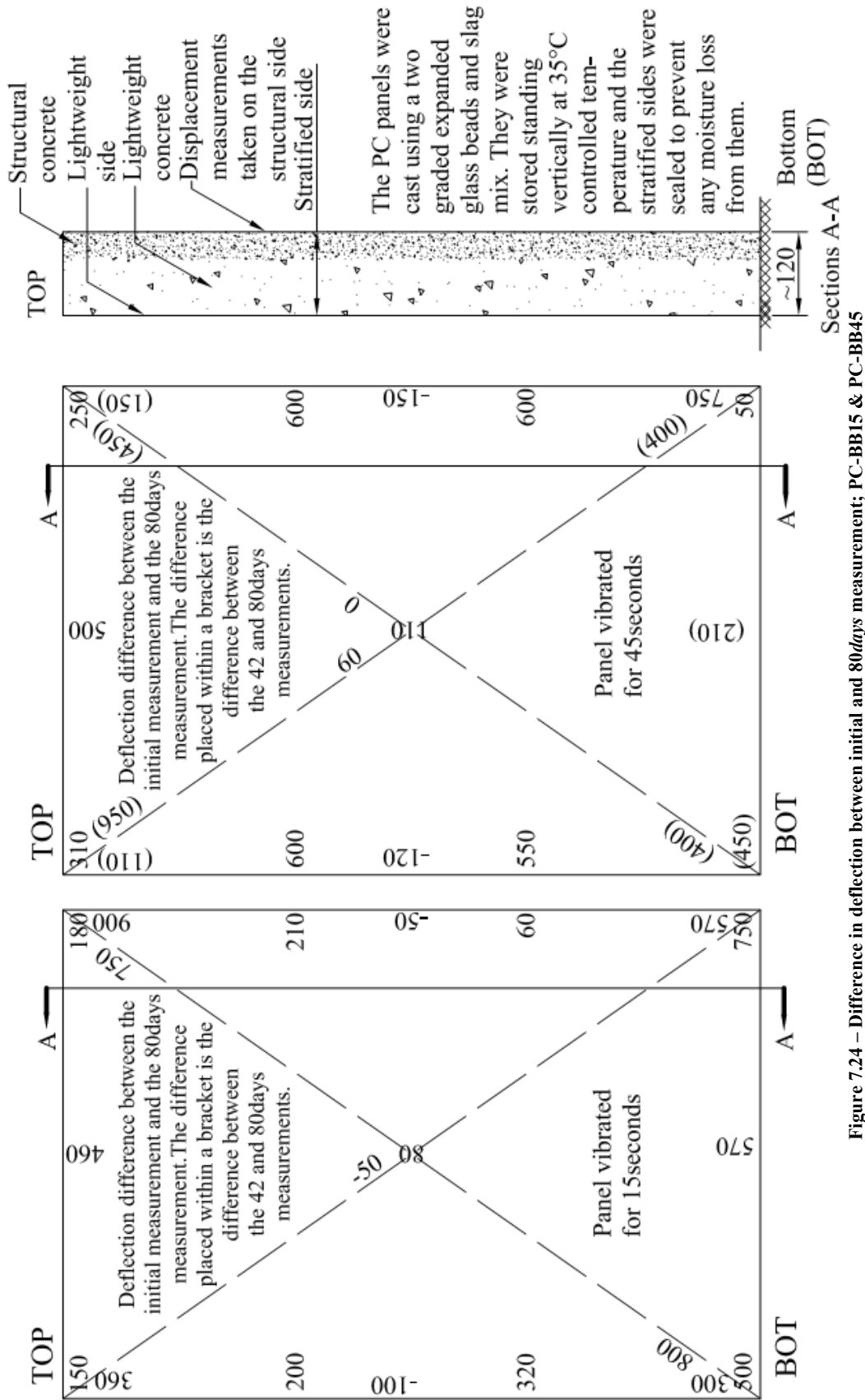


Figure 7.24 – Difference in deflection between initial and 80days measurement; PC-BB15 & PC-BB45

On Figure 7.24 the difference that is placed within a bracket is the difference between the 42 and 80days were initial measurement was not taken

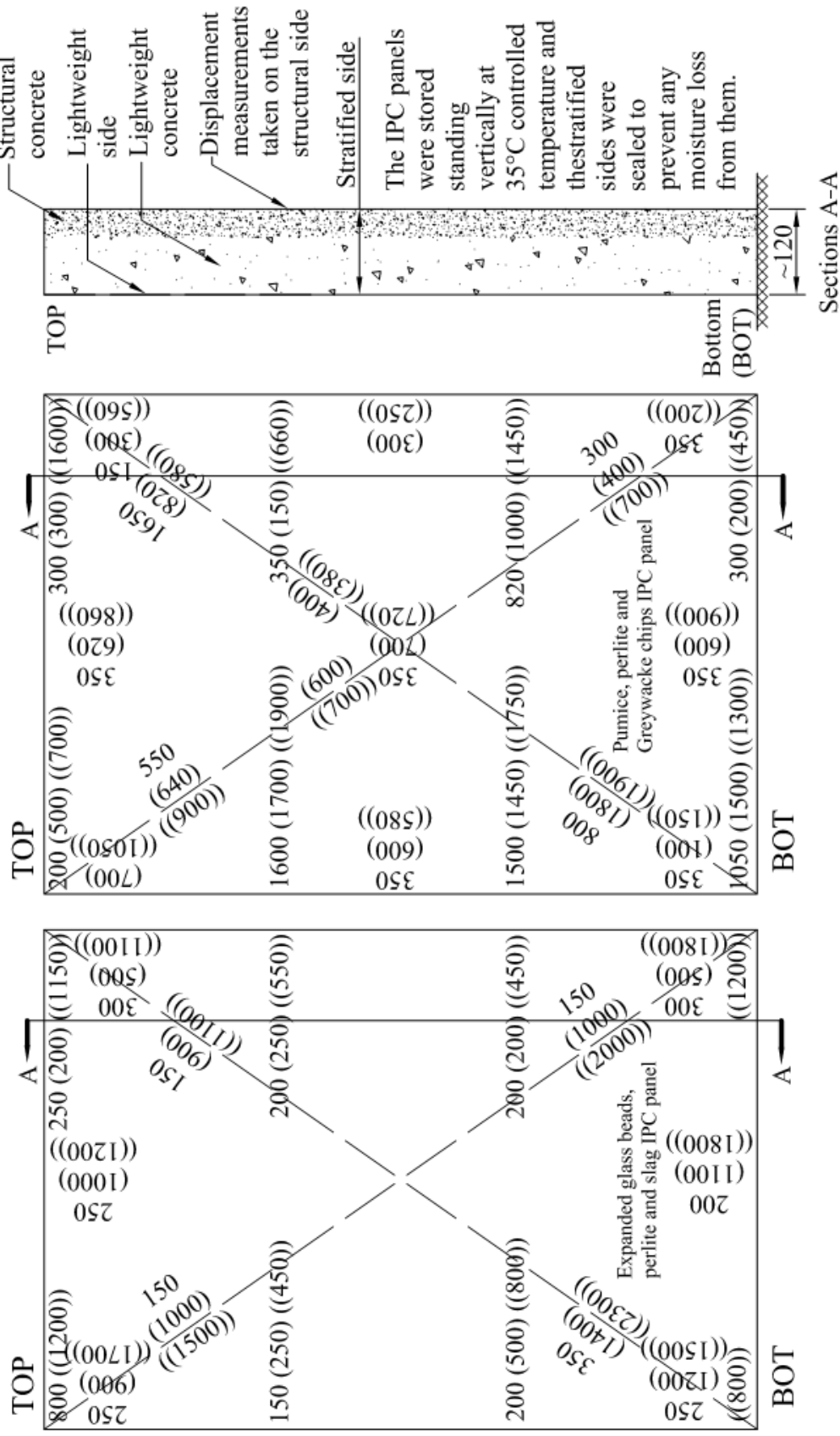


Figure 7.25 - Measured displacement on panels IPC-BB and IPC-PUM2

On Figure 7.25 the number outside the bracket is the initial measurement, the number in one bracket is the 42days measurement and the number in the two brackets is the 80days measurement

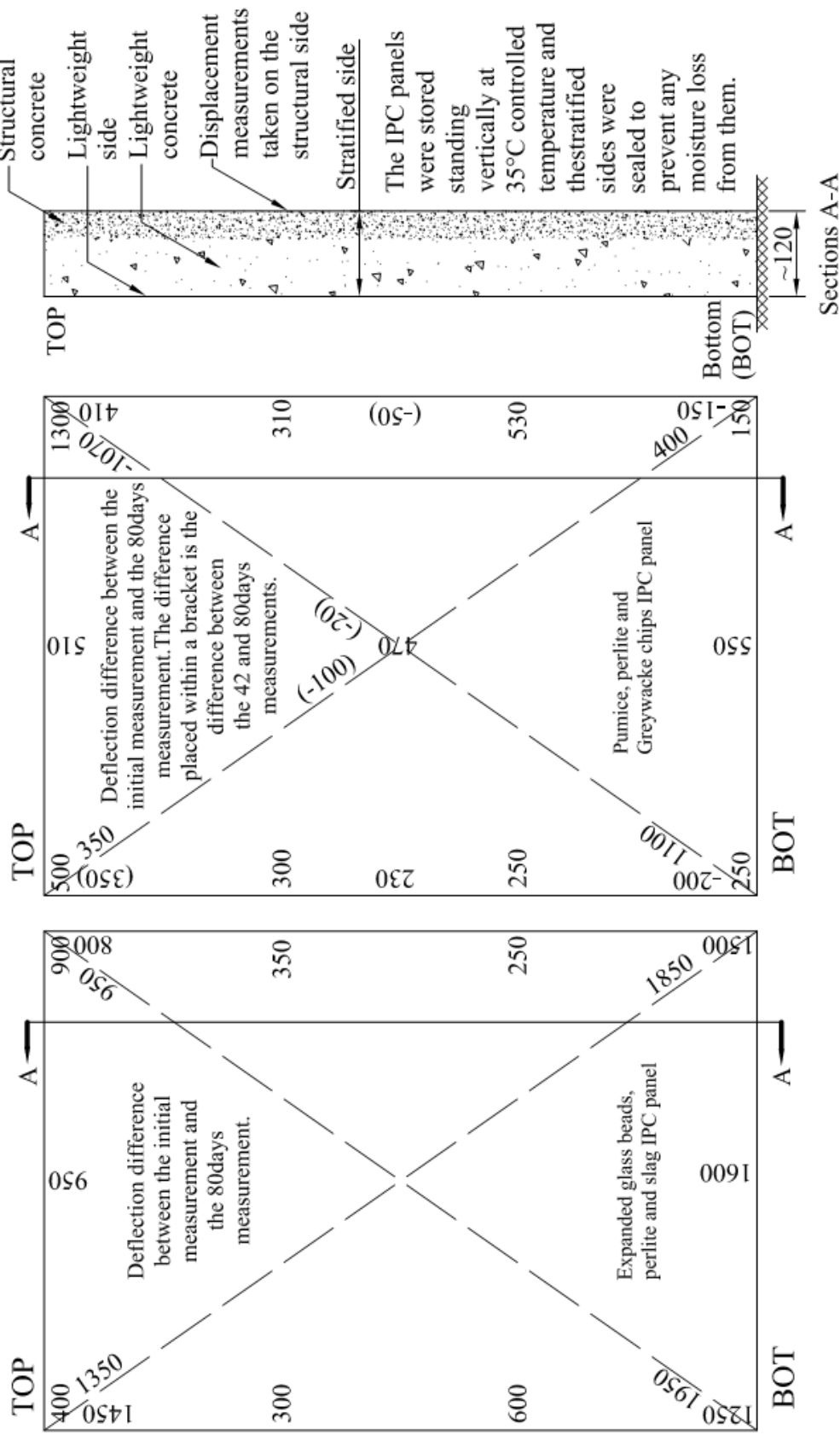
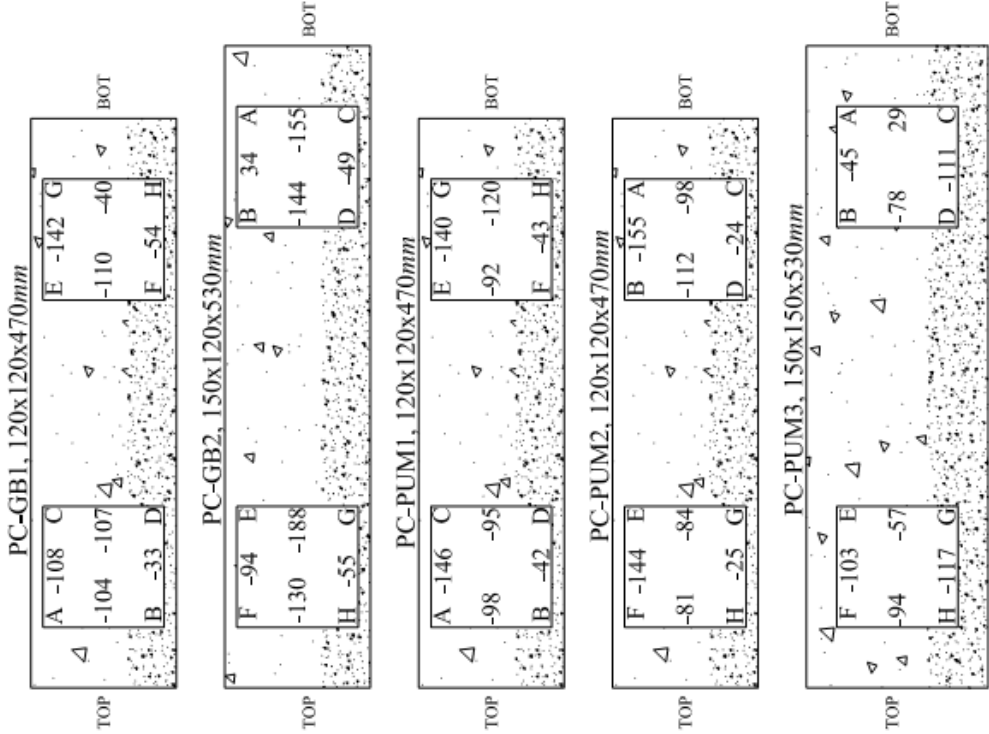


Figure 7.26 - Difference in deflection between initial and 80days measurement; IPC-BB & IPC-PUM2

On Figure 7.26 the difference that is placed within a bracket is the difference between the 42 and 80days were the initial measurement was not taken

7.6.2.2 Strips

Difference between the initial
and the 99 days reading



Difference between the initial
and the 229 days reading

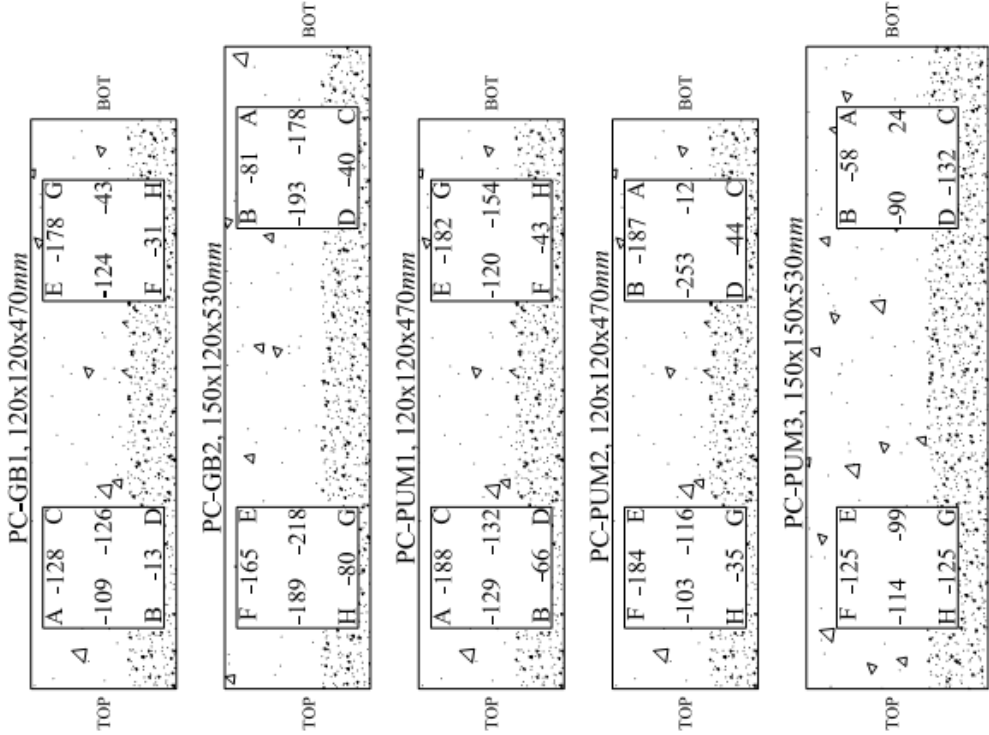


Figure 7.27 – Location of gages and difference in initial and 99/229days length [micrometers]

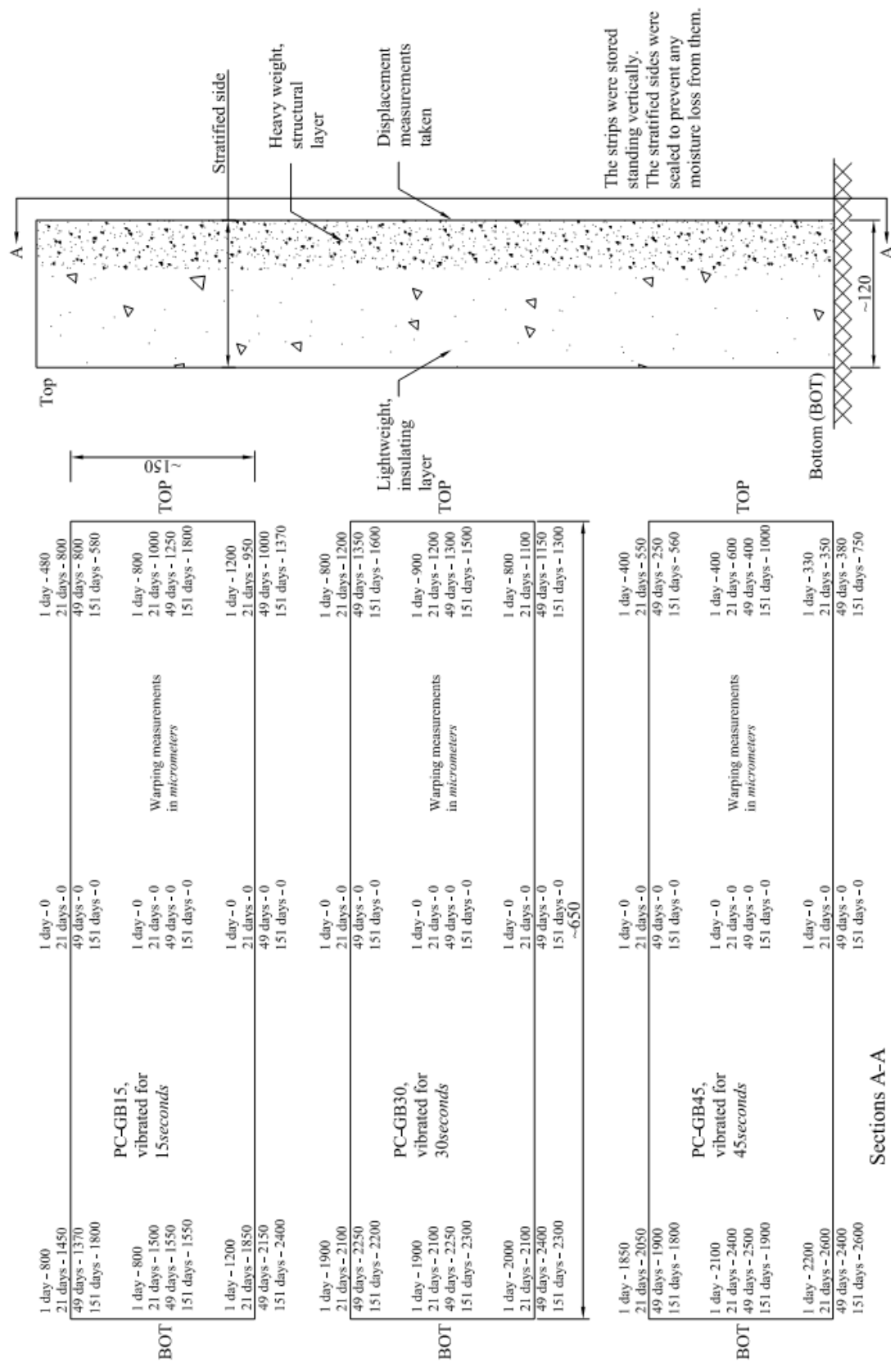


Figure 7.28 – Warping measurements of the strips PC-GB15, 30 & 45

Table 7.10 – Difference in deflection with time for the panel strips

Strip	Location	Deflection [micrometers]	Δ 21days	Δ 49days	Δ 151days
PC-GB15	Bottom	Line 1	650	570	1000
		Line 2	700	750	750
		Line 3	650	950	1200
		Average	667	757	983
	Top	Line 1	320	320	100
		Line 2	200	450	1000
		Line 3	-250	-200	170
		Average	90	190	423
PC-GB30	Bottom	Line 1	200	350	300
		Line 2	200	350	400
		Line 3	100	300	300
		Average	167	367	333
	Top	Line 1	400	550	800
		Line 2	300	400	600
		Line 3	300	350	500
		Average	333	433	633
PC-GB45	Bottom	Line 1	200	50	-50
		Line 2	300	400	-200
		Line 3	400	200	400
		Average	300	217	50
	Top	Line 1	150	-150	160
		Line 2	200	0	600
		Line 3	20	50	420
		Average	123	-33	393

Table 7.11 – Calculated deflection for the panel strips

Strip	Location	Deflection [%]	Δ 21days	Δ 49days	Δ 151days
PC-GB15	Bottom	Maximum	0.108	0.146	0.185
		Average	0.103	0.116	0.151
	Top	Maximum	0.049	0.069	0.154
		Average	0.014	0.029	0.065
PC-GB30	Bottom	Maximum	0.031	0.062	0.051
		Average	0.026	0.056	0.062
	Top	Maximum	0.062	0.085	0.123
		Average	0.051	0.067	0.097
PC-GB45	Bottom	Maximum	0.062	0.062	0.062
		Average	0.046	0.033	0.008
	Top	Maximum	0.031	0.008	0.092
		Average	0.019	-0.005	0.061

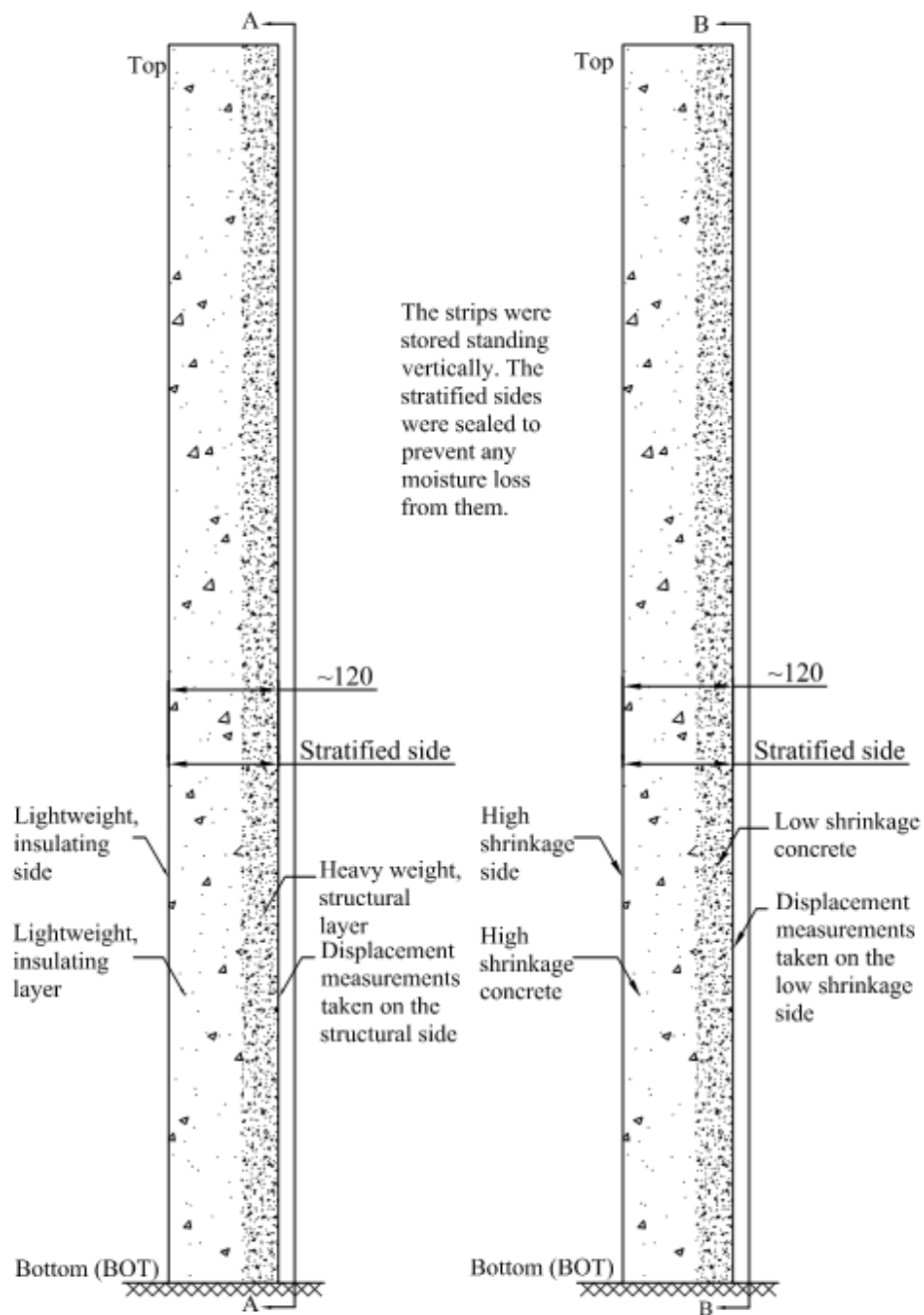


Figure 7.29 – Sections of slender strips used to measure the amount of deflection over time

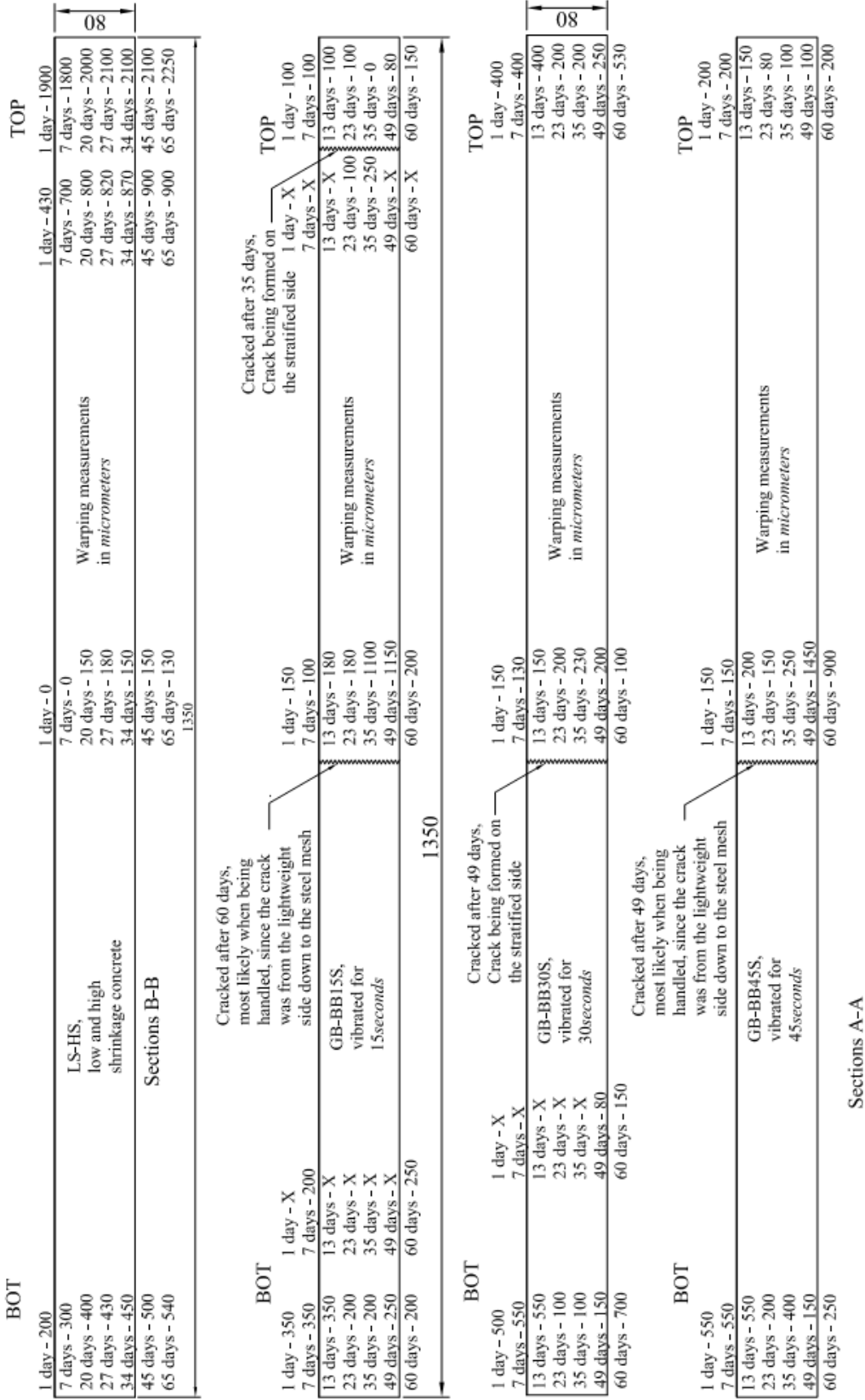


Figure 7.30 - Deflection measurements of the slender strips PC-BB15S, 30S and 45S, as well as LS-HS

Table 7.12 – Change in deflection with time for the slender strips [micrometers]

Strip	Location	Δ 7days	Δ 13days	Δ 23days	Δ 35days	Δ 49days	Δ 60days
PC-BB15S	Bottom	0	0	-150	-150	-100	-150
	Middle	-50	30	30	950	1000	50
	Top	0	0	0	-100	-20	50
				Stress crack			Handling crack
PC-BB30S	Bottom	50	50	-400	-400	-350	200
	Middle	-20	0	50	80	50	-50
	Top	0	0	-200	-200	-150	130
						Stress crack	
PC-BB45S	Bottom	0	0	-350	-150	-400	-300
	Middle	0	50	0	100	1300	750
	Top	0	-50	-120	-100	-100	0
						Handling crack	
		Δ 7days	Δ 20days	Δ 27days	Δ 34days	Δ 45days	Δ 65days
LS-HS	Bottom	100	200	230	250	300	
	Middle	0	150	180	150	150	
	Top	-100	100	200	200	200	

Table 7.13 - Calculated change in deflection for the slender strips [%]

Strip	Location	Δ 7days	Δ 13days	Δ 23days	Δ 35days	Δ 49days	Δ 60days
PC-BB15S	Bottom	0.000	0.000	-0.011	-0.011	-0.007	-0.011
	Middle	-0.004	0.002	0.002	0.070	0.074	0.004
	Top	0.000	0.000	0.000	-0.007	-0.001	0.004
					Stress crack		Handling crack
PC-BB30S	Bottom	0.004	0.000	-0.030	-0.030	-0.026	0.015
	Middle	-0.001	0.002	0.004	0.006	0.004	-0.004
	Top	0.000	0.000	-0.015	0.015	-0.011	0.010
						Stress crack	
PC-BB45S	Bottom	0.000	0.000	-0.026	-0.011	-0.030	-0.022
	Middle	0.000	0.004	0.000	0.007	0.096	0.056
	Top	0.000	-0.004	-0.009	-0.007	-0.007	0.000
						Handling crack	
		Δ 7days	Δ 20days	Δ 27days	Δ 34days	Δ 45days	Δ 65days
LS-HS	Bottom	0.007	0.015	0.017	0.019	0.022	0.025
	Middle	0.000	0.011	0.013	0.011	0.011	0.010
	Top	-0.007	0.007	0.015	0.015	0.015	0.026

8 Thermal Properties

Heating residential buildings is essential in colder climates such as New Zealand. When buildings experience a large temperature range on a daily basis, it is important that heat can be retained during the day and released internally when temperatures drop over night. Buildings in these countries should therefore have suitable thermal insulating properties and thermal capacity to stabilize internal temperatures.¹

Thermal properties of concrete are assessed by examining the following properties:

- **Thermal conductivity**, which measures the ability of a material to conduct heat and is defined as the ratio of heat flux to temperature gradient
- **Specific heat** of a material is the amount of heat per unit mass required to change the temperature by one degree
- **Thermal mass**, which is the ability of material to absorb and store thermal energy using its mass
- **Total thermal resistance (R-value)** is a measure of a products insulating ability, calculated from the thermal conductivity and the thickness of the material ($R\text{-value} = \text{thickness/thermal conductivity}$)

The thermal conductivity of concrete mainly depends on its aggregate type and the degree of saturation. The moisture content of concrete affects the thermal conductivity where moist concrete has higher thermal conductivity than dry concrete. Density does not considerably affect the conductivity of ordinary concrete but thermal conductivity of lightweight concrete increases as its density increases, due to the low conductivity of air. The binder type used also affects the thermal performance, since inorganic polymer gives lower thermal conductivity than similar Portland cement binder. Saturated structural concrete has a thermal conductivity between $1.4\text{--}3.6\text{W/mK}$, while it is difficult to get the thermal conductivity value below 0.2W/mK for lightweight concrete.^{2,3}

The specific heat represents the heat capacity of concrete. Specific heat is little affected by the mineralogical character of the aggregate, but is considerably increased by an increase in the moisture content of concrete. Ordinary concrete has relatively low specific heat, generally between $0.5\text{--}1.17\text{kJ/kgK}$, whereas specific heat of water is 4.2kJ/kgK and timber has 2.1kJ/kgK .^{4,5}

Traditionally concrete is considered as a poor insulator with good thermal mass, or fabric energy storage. Concrete will absorb thermal energy, store it, and release it when the internal temperature drops below that of the concrete.⁶ Adobe, earth, stone, concrete and water, that is, materials with high specific heat, high density and relatively low thermal conductivity all have good thermal mass.⁷

¹ Bobrowski J. 1978:5

² Neville, A.M. 1995:374-5

³ Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

⁴ Mackechnie, J.R. 2006

⁵ Neville, A.M. 1995:377

⁶ Cement and Concrete Association of Australia. 2005:1

⁷ Bellamy, L. 2007

The thermal performance of buildings is often assessed by using the R-value, which is a measure of thermal resistance or products insulating ability. A building product with high R-value has more resistance to heat loss in winter and heat gain in summer than a product with low R-value. The R-values requirements in New Zealand are dependent on the building component, as lower R-values are required for building components in a solid construction. New Zealand is divided into three climate zones with different R-values requirements:⁸

- Zone 1 – Auckland and Northland with minimum R-value of $0.6\text{m}^2\text{K/W}$
- Zone 2 – Remainder of the North Island with minimum R-value of $0.6\text{m}^2\text{K/W}$
- Zone 3 – South Island and Central North Island with minimum R-value of $1\text{m}^2\text{K/W}$

These values are increasing in 2007 and 2008 to $0.8\text{m}^2\text{K/W}$ for zone 1, $1.0\text{m}^2\text{K/W}$ for zone 2 and $1.2\text{m}^2\text{K/W}$ for zone 3.⁹ To combine good thermal storage and insulation, Bellamy and McSaveney¹⁰ proposed the concept of the variable density concrete panel. The concept is shown on Figure 8.1 and utilises a dense thermal mass layer on the inside and a lightweight, insulating layer on the outside.

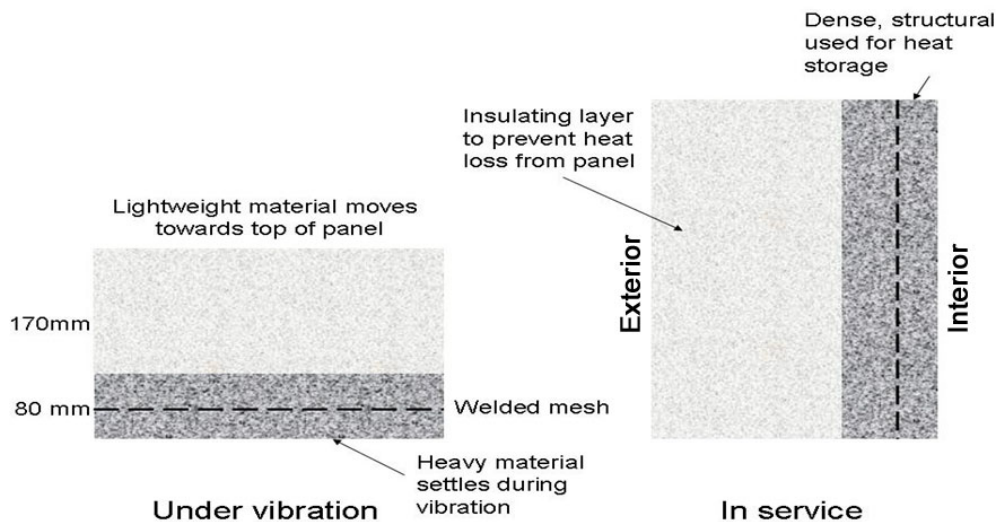


Figure 8.1 - Illustration of variable density concrete panel¹¹

The technical objectives with respect to thermal performance for stratified concrete are listed in Table 8.1. The thicknesses of the top and bottom layers were estimated to get optimum thermal performance the panels.

Table 8.1 – Technical objectives for stratified concrete¹²

Material Property	Top Layer	Bottom Layer
Thickness [mm]	170	80
Thermal Conductivity [W/mK]	<0.25	1.00-1.25

⁸ NZS 4218, 2004

⁹ CCANZ, 2007

¹⁰ Bellamy, L.A. & McSaveney, L.G. 2003

¹¹ Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007

¹² Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007

Specific Heat [MJ/m^3K]	0.75-1.25	2.00-3.00
R-value panel [m^2K/W]	0.8-1.0	

A non-steady state method of thermal analysis (Transient Plane Source (TPS)) was used to provide rapid measurements of thermal performance. It is a modern technique that gives information about the thermal conductivity, thermal diffusivity and specific heat per unit volume of the material under study. Here, a method called Hot Disk Thermal Constants Analyser¹³ was used, that is based on the use of a transiently heated plane sensor.

The thermal properties were measured on three types of samples, cast from the same mix design containing Portland cement, two grades of expanded glass beads (2-4 and 0.5-1mm) and slag:

- **T1** – Standard 100Ø cylinders were cut down vertically in the middle when demoulded and placed in a drying environment. The thermal properties were measured in the insulating and structural layer, between the two half cylinders as shown on Figure 8.2
- 250mm high and 150mm diameter cylinders were cast to estimate the thermal performance of a 250mm thick variable density panel. These cylinders were cut after being fog cured for 21days when they were placed in a drying environment. The cylinders were cut in two ways:
 - **T2** – Vertically into 4 equally sized samples, being a quarter of a cylinder, where the thermal properties were measured on 9 lines up the cylinder as shown on Figure 8.3
 - **T3** – Half a cylinder cut horizontally into 50mm high slices where the thermal properties were measured between the slices as shown on Figure 8.4

For comparison, some inorganic polymer cement concrete samples of type T2 were cast and tested by Mackechnie at the University of Canterbury.¹⁴

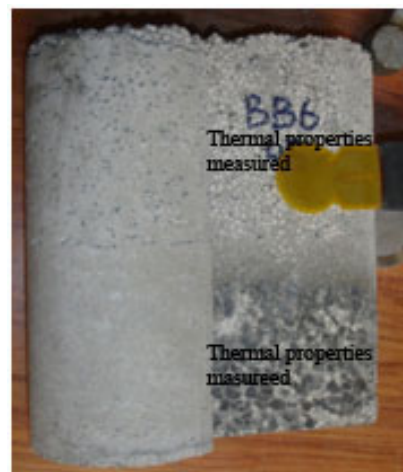


Figure 8.2 – Samples T1

¹³ Gustafsson, S. 2005

¹⁴ Mackechnie, J.R. 2007

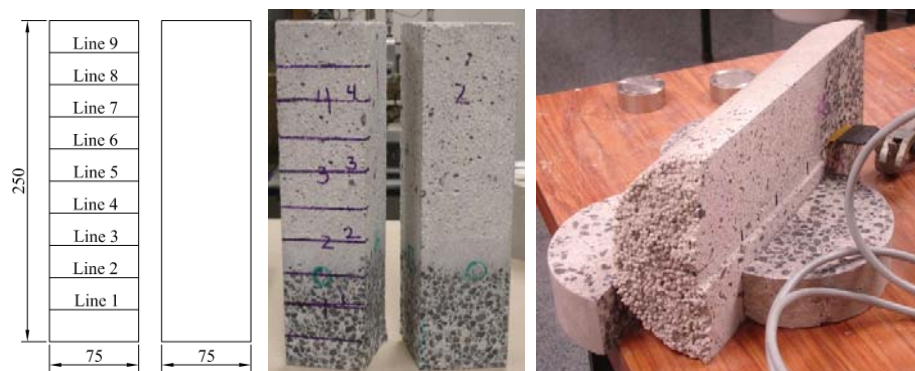


Figure 8.3 – Samples T2

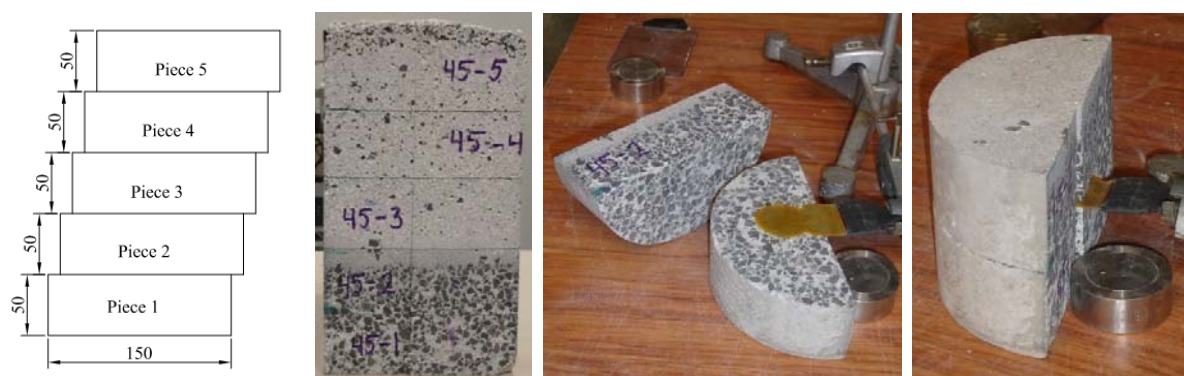


Figure 8.4 – Samples T3

8.1 Results and analysis

The thermal conductivity (TC), specific heat (SH) and density are listed in Table 8.2 and Table 8.3 for all the measured samples as well as the calculated R-value for a 250mm thick variable density wall. For the T2 samples every second value measured is listed, that is, on lines 1, 3, 5, 7 and 9, but the R-value is calculated by using all measured thermal conductivity values.

Table 8.2 – The thermal conductivity (TC), specific heat (SH) and density of the T1 samples

Sample	Drying		Insulating	Structural	R-value [m^2K/W]
T1 Sample 1 Good stratification	14days	TC [W/mK]	0.2374	1.035	<u>0.79</u>
		SH [MJ/m^3K]	0.5021	1.622	
	28days	TC [W/mK]	0.2471	0.8409	<u>0.78</u>
		SH [MJ/m^3K]	0.5493	1.059	
T1 Sample 2 Good stratification	14days	TC [W/mK]	0.2591	0.9447	<u>0.74</u>
		SH [MJ/m^3K]	0.5449	1.610	
	28days	TC [W/mK]	0.2369	0.9346	<u>0.80</u>
		SH [MJ/m^3K]	0.4717	1.304	

Table 8.3 – The thermal conductivity (TC), specific heat (SH) and density of the T2 and T3 samples

	Drying	On line	1	3	5	7	9	R-value [m ² K/W]
T2 Sample 1 Good stratification	7days	TC [W/mK]	1.167	1.068	0.3754	0.3187	0.3021	0.54
		SH [MJ/m ³ K]	1.195	1.186	0.7749	0.6553	0.6069	
		Density [kg/m ³]	2320	2318	1034	960	848	
	35days	TC [W/mK]	1.395	1.321	0.3463	0.3165	0.2819	0.56
		SH [MJ/m ³ K]	1.618	1.770	0.7141	0.7229	0.8898	
		Density [kg/m ³]	2302	2294	1001	928	825	
T2 Sample 2 Good stratification	7days	TC [W/mK]	1.503	1.4050	0.382	0.3585	0.3168	0.53
		SH [MJ/m ³ K]	1.541	1.7920	0.7793	0.7861	0.8286	
		Density [kg/m ³]	2192	2146	1047	869	815	
	35days	TC [W/mK]	1.05	0.9597	0.335	0.2757	0.2498	0.64
		SH [MJ/m ³ K]	1.076	1.1610	0.7371	0.7109	0.6326	
		Density [kg/m ³]	2172	2123	1013	835	791	
	Drying	Between slices	1-2	2-3	3-4	4-5	5-6	R-value [m ² K/W]
T3 Sample 1 Poor stratification	7days	TC [W/mK]	1.557	0.8842	0.7348	0.5617	0.5154	0.40
		SH [MJ/m ³ K]	1.384	1.052	0.9495	1.144	1.047	
		Density [kg/m ³]	1677	1598	1349	1214	1009	
	35days	TC [W/mK]	1.183	0.6258	0.5215	0.4091	0.3529	0.56
		SH [MJ/m ³ K]	1.904	0.9579	1.38	0.8636	1.137	
		Density [kg/m ³]	1625	1552	1291	1148	934	
T3 Sample 2 Good stratification	7days	TC [W/mK]	1.806	0.8312	0.4934	0.3731		0.43
		SH [MJ/m ³ K]	1.468	1.684	0.8797	1.06		
		Density [kg/m ³]	2215	1651	962	847		
	35days	TC [W/mK]	1.335	0.6201	0.3146	0.2428		0.65
		SH [MJ/m ³ K]	1.698	1.644	0.8538	0.6586		
		Density [kg/m ³]	2160	1586	881	766		
	Drying	Line	1 62.5mm	2 62.5mm	3 62.5mm	4 62.5mm		R-value [m ² K/W]
IPC¹⁵ Sample 1 Good stratification	28days	TC [W/mK]	1.326	0.418	0.281	0.225		0.70
		SH [MJ/m ³ K]	1.338	0.627	0.415	0.453		
		Density [kg/m ³]	2395	1234	955	862		
IPC¹⁶ Sample 2 Moderate stratification	28days	TC [W/mK]	1.184	0.445	0.373	0.251		0.61
		SH [MJ/m ³ K]	2.158	1.167	1.441	1.189		
		Density [kg/m ³]	2305	1447	1310	1074		

The initial objectives were generally not reached, but these mixes were not designed to optimise the thermal performance:

- The thermal conductivity was higher than initially aimed for in the lightweight insulating layer and for most measurements in the structural layer

¹⁵ Mackechnie, J.R. 2007

¹⁶ Mackechnie, J.R. 2007

- The specific heat was lower than initially aimed for in the structural layer as it never reached $2MJ/m^3K$ in the Portland cement concretes and generally in the lightweight layer as well, despite few values being slightly over $0.75MJ/m^3K$
- The R-values were generally much lower than the original objectives

Variable density concrete was found to have significantly lower thermal conductivity in the lightweight insulating layer than in the structural thermal storage layer (Figure 8.5). The thermal conductivity in the structural concrete layer can however drop if there is significant amount of trapped lightweight material within the layer. In the lightweight insulating concrete, the thermal conductivity increases as it gets closer to the structural concrete layer, as the paste between the lightweight particles increases.

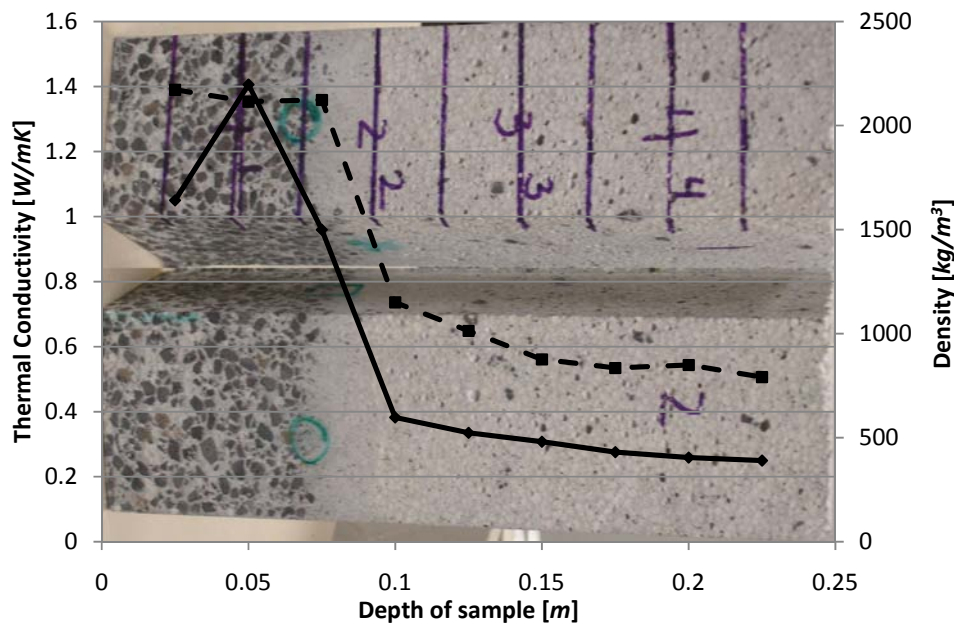


Figure 8.5 – Depth of variable density concrete versus thermal conductivity (whole) and density (dashed line)

Variable density concrete was found to have significantly lower specific heat in the lightweight insulating layer than in the structural thermal storage layer (Figure 8.6). As mentioned before, the specific heat within the structural layer was lower than what was aimed for, decreasing the thermal storage capacity of the structural concrete. This can be related to lightweight material getting trapped within the structural layer, decreasing the specific heat.

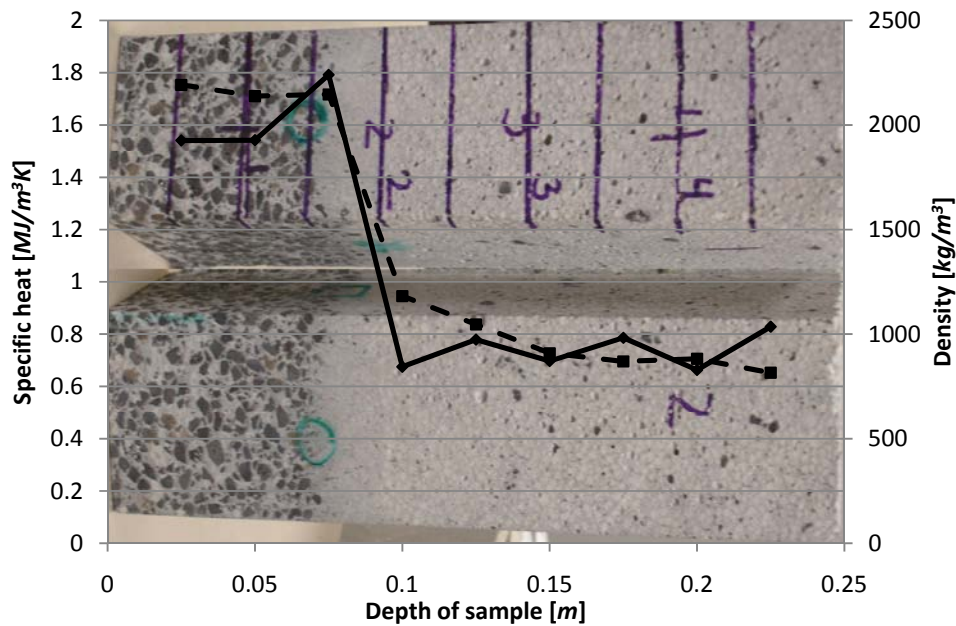


Figure 8.6 - Depth of variable density concrete versus specific heat (whole) and density (dashed line)

There were several factors that influenced the thermal performance as discussed below.

8.1.1 **Moisture content**

As the moisture content within the concrete decreased, the thermal conductivity was found to decrease. From Table 8.2 and Table 8.3 it can be found that the density of the concrete generally decreases after being dried for a longer period of time, indicating moisture loss from the concrete. As the density and the moisture content decreases, the thermal conductivity decreases as well, as shown on Figure 8.7. On samples T1, where the thermal conductivity tends to increase slightly as well as decrease in the insulating layer, measurements were taken at one point within the layer, making the results less accurate.

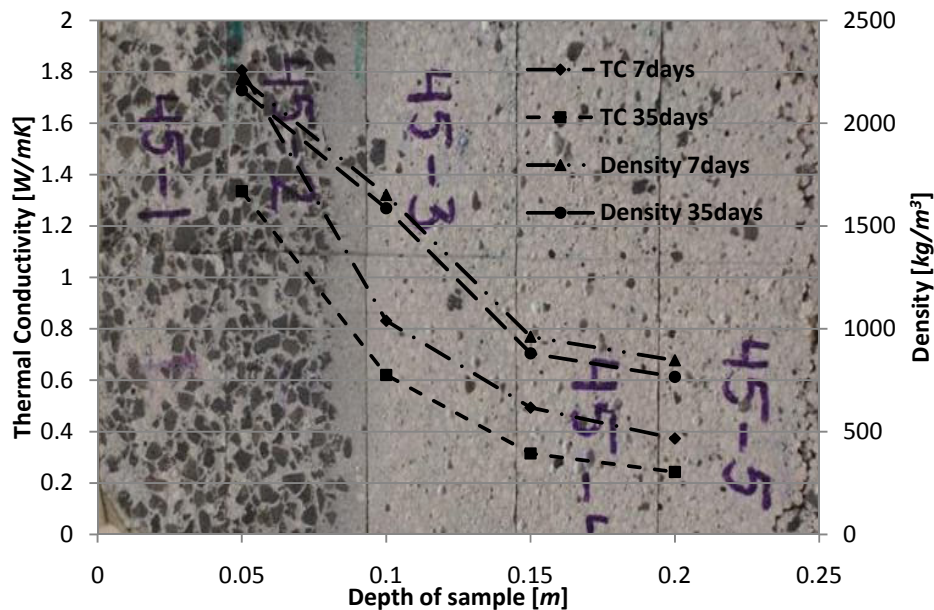


Figure 8.7 – Decreased thermal conductivity (TC) with decreased density and moisture content at 35days

8.1.2 Degree of hydration

Samples T1 were cut as they were demoulded and placed in a drying environment whereas samples T2 and T3 were wet cured for 21days before cut and dried. The measured thermal conductivity is significantly higher on samples T2 and T3 than on samples T1 as listed in Table 8.2 and Table 8.3. Higher thermal conductivity leads to lower R-values for the stratified concrete. The thermal conductivity for the 21days wet cured samples, T2 and T3, is usually above $0.30W/mK$, whereas the thermal conductivity for samples T1 is usually below $0.25W/mK$. When concrete is wet cured, enough water is provided to hydrate the cement making the concrete denser. As the concrete gets denser, the thermal conductivity increases as air voids are replaced by paste, but air has a much lower thermal conductivity.

The effect of thermally curing the Portland cement concretes was not assessed, although, it is likely to improve thermal performance of the concrete by producing a coarser microstructure similar to reduced moist curing.

8.1.3 Density of the concrete

A linear relationship between thermal conductivity and the density was found for the well stratified samples as plotted on Figure 8.8. As the density of the concrete decreases, so does the thermal conductivity. The thermal conductivity is clearly lower for the lightweight concrete, having a density between 700 and $1300kg/m^3$ than for the structural concrete having a density above $2100kg/m^3$. The thermal conductivity for the lightweight concrete varies between 0.23 and $0.49W/mK$, which is as mentioned before, higher than what was aimed for in the beginning (Table 8.1). The thermal conductivity for the structural concrete was also higher than what was hoped for despite few measurements being within the right range. As mentioned before, these mixes were not designed for optimising the thermal performance.

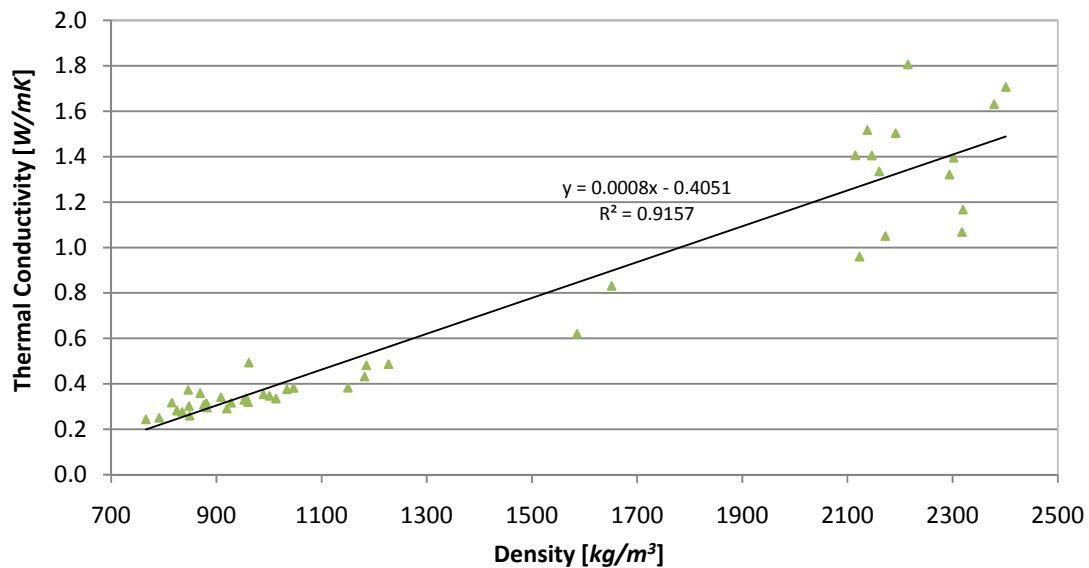


Figure 8.8 – Relationship between thermal conductivity and density for well stratified samples

8.1.4 Amount of stratification

On Figure 8.9, two cylinders cast by using the same mix design, cured under the same conditions and measured simultaneously are viewed. One of them is poorly stratified whereas the other one is well stratified. The poorly stratified cylinder has R-value of $0.47\text{m}^2\text{K/W}$ while the well stratified one has R-value of $0.65\text{m}^2\text{K/W}$. The R-value of a well stratified sample is therefore significantly higher than for a poorly stratified sample. When the variable density concrete is poorly stratified, the thermal conductivity in the lightweight concrete layer increases as there is significant amount of trapped normal/heavyweight material among the lightweight aggregate, forming thermal bridges. The thermal conductivity reduces slightly in the structural concrete layer as more trapped lightweight aggregate is between the normal/heavyweights aggregate. The reduction in thermal conductivity in the structural layer is not as large as the increase in the lightweight insulation concrete layer. The lightweight insulating layer is also thicker than the structural layer reducing the R-value even more as the R-value is found by dividing the thermal conductivity with the thickness.

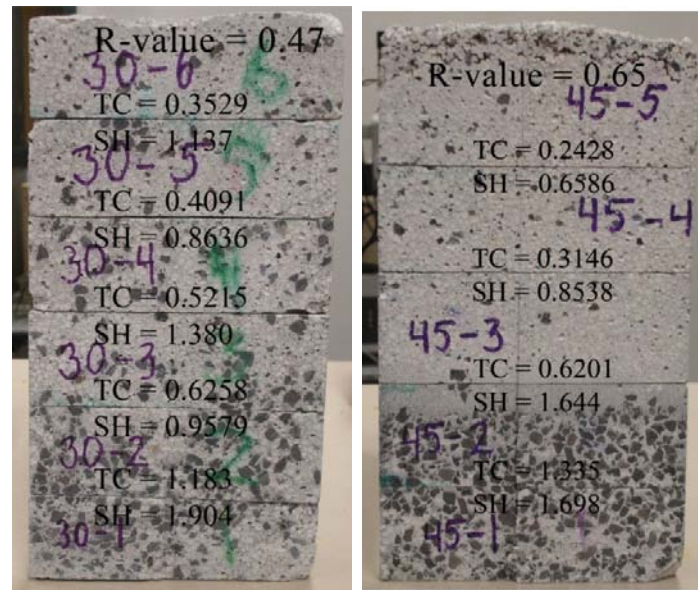


Figure 8.9 – Effect of stratification on thermal performance of the variable density concrete

8.1.5 Binder used

It had already been shown by Mackechnie et al¹⁷ that using inorganic polymer cement (IPC) instead of Portland cement (PC) provided concrete with lower thermal conductivity as shown on Figure 8.10. Here the IPC samples generally had lower thermal conductivity than the PC concretes as listed in Table 8.3. The IPC lightweight concrete provided thermal conductivity below $0.25 W/mK$ when well stratified, which was not the case for the PC concretes.

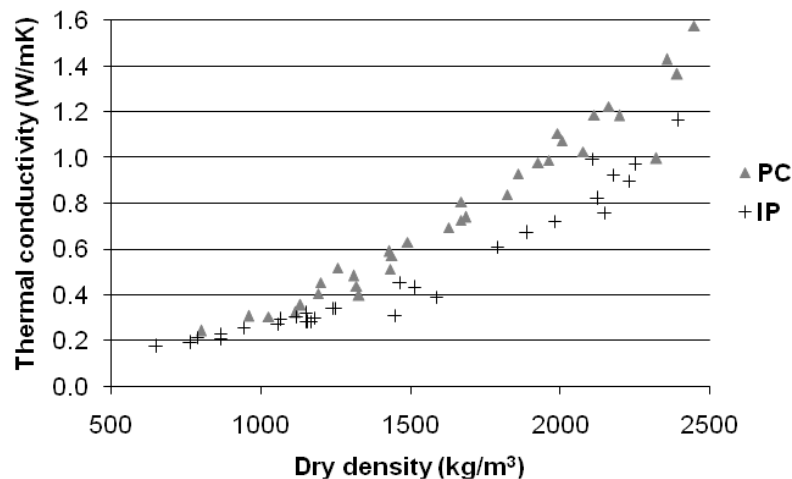


Figure 8.10 – TC versus density of inorganic polymer cement (IP) and Portland cement (PC) concrete¹⁸

¹⁷ Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

¹⁸ Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007

8.2 Other factors affecting thermal performance

There are several factors that affect the thermal performance of concrete but were not included in this survey of the thermal performance of the variable density concrete.

Aggregate materials being used as the thermal performance was only measured on one specific mix design. Using other lightweight aggregates with different material properties as well as lower density could improve the thermal properties of the variable density concrete.

Previous research shows that thermal conductivity values do not reach equilibrium until after more than 90days of drying. Longer wet curing of concrete increases the time it takes for the concrete to dry. Mackechnie¹⁹ tested the affect different curing had on the variable density concrete. Samples were cured at 20°C for the first 24hours to simulate laboratory curing and at 60°C simulating curing performed at a precast yard. The samples were then either wet cured for 1 or 7days before being placed in a drying environment where the thermal properties were tested after 7, 14, 28 and 60days. The results are shown on Figure 8.11 finding that it took a longer time for the thermal conductivity to reach equilibrium if the concrete was wet cured for a longer time.

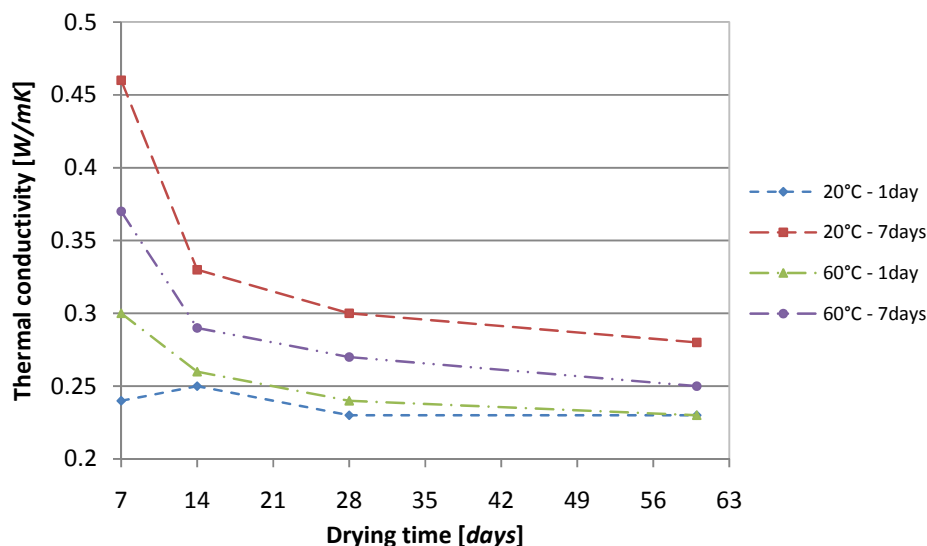


Figure 8.11 – Thermal conductivity versus drying time of differently cured samples²⁰

The thermal conductivity in this research was measured after 28 and 35days of drying when the concrete is not fully dried therefore giving higher thermal conductivity values than a fully dried sample.

Wall R-values typically include surface resistances but this was not tested or included here. It has however been found that the surface resistances are approximately 0.12 and 0.03m²K/W for the inside and outside surfaces respectively.²¹

¹⁹ Mackechnie, J.R. 2007

²⁰ Mackechnie, J.R. 2007

²¹ Bellamy, L. 2007a

8.3 Conclusion

The thermal conductivity and the specific heat are significantly lower in the lightweight insulating concrete layer than in the structural thermal storage layer. The initial objectives were generally not reached, and further development is required to improve thermal performance.

- The thermal conductivity was generally higher than what was aimed for initially
- The specific heat was generally lower than what was aimed for initially
- The calculated R-values were lower than the original objectives ($>0.8\text{m}^2\text{K/W}$)

These mixes were not designed to optimise the thermal performance and were tested before the concrete was fully dried increasing the thermal conductivity and thereby the R-values.

Factors affecting the thermal conductivity and thereby the R-value, which were noticed from these measurements were:

- Moisture content reductions caused a decrease in thermal conductivity
- Increased cement hydration increased thermal conductivity
- Lower density reduced thermal conductivity
- Improved stratification increased the overall R-value
- Inorganic polymer concretes had lower thermal conductivity than Portland cement concretes

By optimising the mix design, the thermal performance aimed for in the beginning could be reached. This could be done by using different aggregate materials and/or inorganic polymer cement instead of Portland cement.

8.4 References

- Bellamy, Larry. 2007. Lecture notes in ENCI 621, *Concrete Materials and Practice*, 4th April. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Bellamy, Larry. 2007a. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Bellamy, L.A. & McSaveney, L.G. 2003. “*FRST – Future Building Systems Research Proposal*”, University of Canterbury, Christchurch, New Zealand.
- Bobrowski, Jan. 1978. *FIP State of Art Report: Principles of thermal insulation with respect to lightweight concrete*. Cement and Concrete Association, Wexham Springs, Brittan.
- CCANZ, Cement & Concrete Association of New Zealand. 2007, December. *Information Bulletin: IB 87. Concrete Masonry, Compliance with Clause H1 – Energy efficiency*. CCANZ, Cement & Concrete Association of New Zealand, Wellington, New Zealand.
- Cement and Concrete Association of Australia. 2005. *Thermal benefits of ‘solid’ construction*. Australia.
- Gustafsson, S. 2005. “*Hotdisk thermal constant analyzer – Instruction manual version 5.0*”, Gothenburg.
- Mackechnie, J.R. 2006. Lecture notes in ENCI 621, *Concrete Materials and Practice*, second semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- Mackechnie, J.R.; Sævarsdóttir, T. & Bellamy, L.A. 2007. “Stratified Precast Concrete Panels for Buildings.” *Concrete Plant International*, July 2007.
- Neville, A.M. 1995. “*Properties of Concrete*” Longman Group Limited, Longman House, Burnt Mill, Harlow Essex, England.
- NZS, New Zealand Standard. 2004. “*NZS 4218: Energy Efficiency – Small Building Envelope*”. NZS, New Zealand Standard, Wellington, New Zealand.

9 Durability Performance

“Durability is the ability of a material or a structure to withstand the service conditions for which it was designed, for a prolonged period without significant deterioration.”¹ Deterioration that occurs in concrete over time is often associated with transport processes such as:^{2 3}

- **Diffusion** which is the process by which ions (liquid or gas) move through a porous material under the action of a concentration gradient. Diffusion is an important internal transport mechanism for concrete exposed to salts
- **Absorption** is the process where fluid is drawn into a porous, unsaturated material under the action of capillary forces. The amount of capillary suction depends on the pore volume and geometry as well as the saturation level of the concrete. Sorptivity is the rate of movement of wetting front through porous material under the action of capillary forces
- **Permeation** is caused by hydraulic gradient; that is the process of movement of fluids through the pore structure of concrete under an externally applied pressure, as the pores are saturated with the particular fluid. Permeability therefore measures, the capacity of concrete to transfer fluids by permeation and is dependent on the concrete's microstructure and moisture condition as well as the characteristics of the permeating fluid

Durability is not a property of a concrete material but rather the performance of a concrete structure in certain exposure conditions. Permeation of hardened concrete is critical to the transport processes occurring in the pore system of concrete and is often used to assess the durability and service life of concrete.⁴

As the variable density concrete is not expected to be placed in a marine environment, chloride resistance was not considered important. It was more likely to be subject to drier conditions and the following properties were therefore considered:

- **Oxygen permeability** – measured by using the falling head gas permeameters test developed by Ballim⁵ at the University of the Witwatersrand
- **Water sorptivity** – measured by using Ballim's⁶ modified version of Kelham's⁷ sorptivity test

¹ Mackechnie, J.R. 2006

² Mackechnie, J.R. 2006

³ Beushausen, H.D.; Alexander M.G. & Mackechnie, J.R. 2003

⁴ Nilsson, L.O. 2003

⁵ Ballim, Y. 1991

⁶ Kelham, S. 1988

⁷ Ballim, Y. 1993

Table 9.1 - The durability was measured on cylinder slices gained from different mix designs

Oxygen permeability and water sorptivity				
Materials	Panel	Sample	Sample preparation	Stratification
PC	Same mix as used in panels PC-BB15 and PC-BB45	PC-BB1	Standard 100Ø stratified cylinders cut into 7 slices approximately 25mm high. Sample no.1 is from the bottom (structural layer) of the cylinder counting up till slice no.7 at the top (insulating layer), Figure 9.1	Good
2-4 GB		PC-BB2		Good
0.5-1 GB		PC-BB3		Very good
Slag		PC-BB4		Very good
Water sorptivity				
Materials	Panel	Sample	Sample preparation	Stratification
PC	Same mix as used in panel PC-GB	PC-GB1	200mm high structural (bottom) and lightweight (top) cylinders cut into 6 slices approximately 25mm high. The cylinders were gained from the 500mm high stratified cylinders described in Chapter 5	Moderate
2-4 GB		PC-GB2		Good
Perlite				
Slag				
PC	Same mix as used in panel PC-PUM	PC-PUM1*	200mm high structural (bottom) and lightweight (top) cylinders cut into 6 slices approximately 25mm high. The cylinders were gained from the 500mm high stratified cylinders described in Chapter 5	Moderate
Pumice		PC-PUM2		Moderate
Perlite				
GW				

The materials are: PC – Portland cement; 2-4 GB – 2-4mm expanded glass beads; 0.5-1 GB – 0.5-1mm expanded glass beads; GW – greywacke chips

*Due to mistake when batching 8-13mm aggregate was used instead of 6mm stones

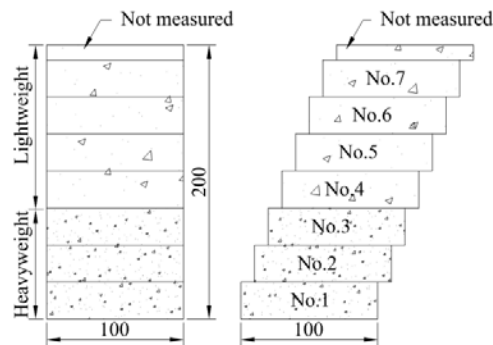


Figure 9.1 – Sample used to measure the oxygen permeability

Suggested ranges for durability classification of concretes are listed in Table 9.2, where OPI is a permeability index.

Table 9.2 – Suggested ranges for durability classification using index values⁸

Durability Class	OPI (log scale)	Sorptivity (mm/√h)
Excellent	>10	<6
Good	9.5-10	6-10
Poor	9.0-9.5	10-15
Very poor	<9.0	>15

As well as measuring the oxygen permeability and the water sorptivity, the surface finish is briefly described after being visually observed.

9.1 Oxygen Permeability

The oxygen permeability index (OPI) gained from the measured samples are listed in Table 9.3. Most of the samples had a permeability index (OPI) between 9 and 9.5, which is classified as concrete with poor permeability properties, according to Table 9.2. All the cylinders had an average OPI value within this range. Having some variation in the test results is normal as the oxygen permeability test assesses the overall micro- and macrostructure of the outer surface of cast concrete. It is particularly sensitive to macro-voids and cracks, since they act as short-circuits for the permeating gas.

Table 9.3 – The permeability index (OPI) for PC-2GB1 till 4

	Sample	PC-BB1		PC-BB2		PC-BB3		PC-BB4	
	Slice	OPI	Density	OPI	Density	OPI	Density	OPI	Density
Bottom	1	9.24	2295	8.84	2051	9.24	2291	9.19	2262
	2	9.21	2311	9.45	2360	9.41	2404	9.30	2388
	3	9.46	2022	9.05	2160	9.71	1676	9.19	2241
	4	9.43	1351	9.27	2170	9.08	1248	9.63	1409
	5	9.41	1131	9.42	1414	9.24	1212	9.26	1253
	6	9.38	1242	9.28	1320	9.21	1016	9.23	1215
Top	7	9.35	1176	9.46	1265	9.30	1142	8.72	1222
	Average	9.35		9.25		9.31		9.22	

The OPI value differed depending on the depth of the cylinder where the measured slice was taken. The OPI value was also found to be dependent on the amount of stratification. All these samples were cast using the same mix design and cured under the same conditions. The low value of slice 1 from PC-BB2 is due to a defect in the sample shown on Figure 9.2.

⁸ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

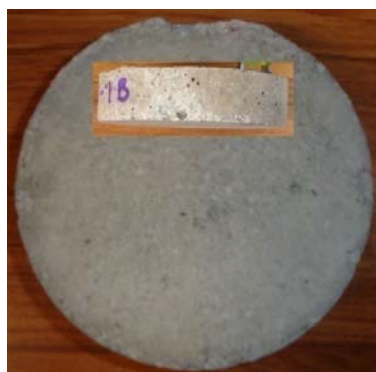


Figure 9.2 – Defect in sample PC-BB2 slice 1, causing low OPI index of 8.84

9.1.1 **Structural and lightweight concrete OPI values**

As mentioned before, the permeability index (OPI) was found between 9 and 9.5 and therefore classified as concrete with poor permeability properties, according to Table 9.2. The structural layer has similar OPI values as the lightweight layer. This can be related to substantial amount of trapped lightweight material within the structural concrete, as shown on Figure 9.3, allowing the permeating gas a way through the gaseous lightweight material.



Figure 9.3 - Substantial amount of trapped lightweight material within the structural layer

The carbonation depth has been found highly related to the OPI value, Table 9.4. That is, as the OPI value decreases the carbonation depth increases. As the carbonation reaches concrete in contact with steel it lowers its pH value causing the steel to corrode.

Table 9.4 – Correlation between the OPI value and the carbonation depth in concrete⁹

OPI	Carbonation depth
8.5	22.5mm
9.0	16.4mm
9.5	10mm

The low OPI value of the lightweight layer is not of as high concern as the low OPI value of the structural layer, as the structural layer includes steel mesh but not the lightweight layer. As the OPI value varies between 9.05 and 9.46 for non defected structural concrete, a 20mm cover depth

⁹ Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

in the structural layer of the half scale panels is on the boundaries of being sufficient. The New Zealand Standard¹⁰ (NZS 3101) also indicates insufficient cover depth. For an element that is fully exposed within a building except for a brief period of weather exposure during construction, the minimum cover requirement is 25mm for 25MPa concrete and 20mm for 30MPa concrete for a specified intended life of 50years.¹¹ The technical objectives for the variable density panels indicates a strength between 25-35MPa in the structural layer, but as discussed in chapter 6 the compressive strength of the structural layer was usually lower than 25MPa. This should not be a problem in the full scale panels were the proposed cover to reinforcement is 30-40mm.

9.1.2 Amount of stratification

The OPI value behaved differently in the samples that were well or very well stratified and the average OPI values were higher for the well stratified samples than for the ones that were very well stratified. The OPI values for the well stratified samples PC-BB1 & 2 are more consistent over the total depth of the sample cylinder than for the very well stratified samples, PC-BB3 & 4. The amount of stratification therefore affects the OPI value as displayed on Figure 9.4 and Figure 9.5.

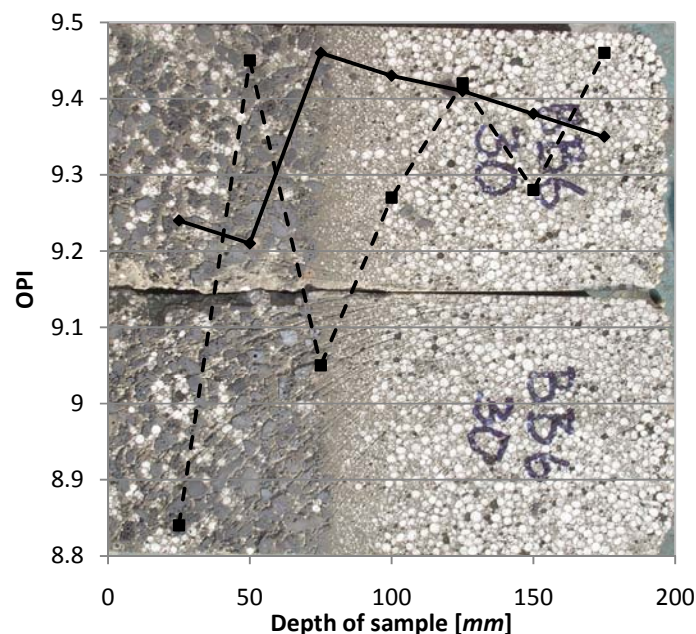


Figure 9.4 – The OPI value for well stratified samples; PC-BB1 (solid line) and PC-BB2 (dashed line)

As mentioned before, the low value of slice 1 from PC-BB2 can be explained by a defect in the sample. The low value of slice 3 from the same mix is harder to explain, as no defect could be found on the sample and the density was not lower than the other slices which could have indicated.

¹⁰ NZS 3101:2006

¹¹ NZS 3101:2006

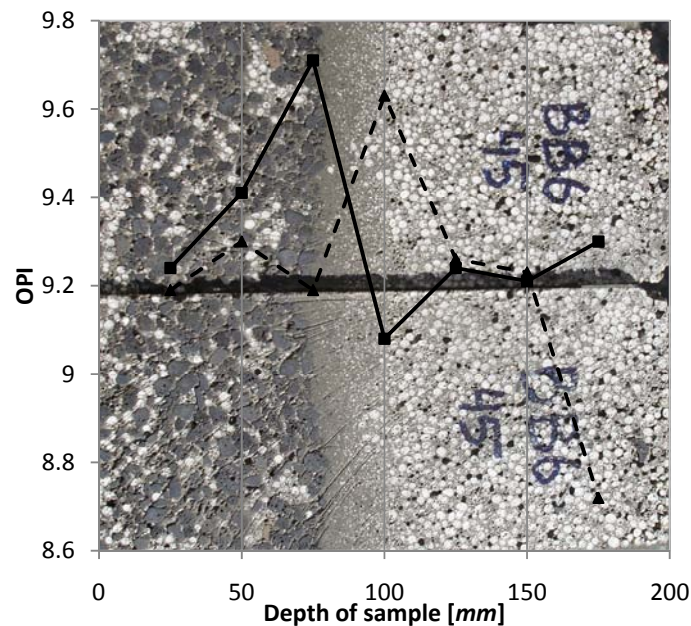


Figure 9.5 – The OPI value for very well stratified samples; PC-BB3 (solid line) and PC-BB4 (dashed line)

No obvious defect was observed on slice 7 from PC-BB4 to explain the low OPI gained. Since the slice is taken from the top of the lightweight layer of a very well stratified sample it was assumed that the slice had lost more paste than other top slices. This was not the case as the density of slice 7 from PC-BB4 was similar to other slices from the insulating layer.

On Figure 9.5 the OPI value suddenly increases as the lightweight layer starts after the structural layer, but this is not the case on Figure 9.4. The only difference between these samples is the amount of stratification, as the samples viewed on Figure 9.4 are well stratified whereas the ones on Figure 9.5 are very well stratified, being slightly over vibrated. As the paste separates from the aggregates it builds up between the layers forming a dense layer, where it closes inter connected pathways between pores within the concrete.



Figure 9.6 – Slice 3 from PC-BB3 (left) with OPI of 9.71 and slice 4 from PC-BB4 (right) with OPI of 9.63

9.2 Water Sorptivity

The measured water sorptivity and porosity for all the samples are listed in Table 9.5, Table 9.6 and Table 9.7. Most of the well stratified samples had a sorptivity either below 6, classified as

concrete with excellent absorption resistance or between 6 and 10 having good absorption resistance, according to Table 9.2. The concrete is highly porous, providing easy access for water into the concrete; even the structural concrete has high porosity, due to trapped lightweight material within the layer.

Table 9.5 – Measured sorptivity (S), porosity (P) and saturated density (D) for PC-GB1 and PC-GB2

Sample	PC-GB1*						PC-GB2					
	Structural			Lightweight			Structural			Lightweight		
Slice	S	P	D	S	P	D	S	P	D	S	P	D
1	7.8	25.1	2161	7.6	35.9	1584	6.6	30.3	2376	3.7	59.3	1422
2	7.4	27.6	2104	7.7	34.8	1865	6.5	30.1	2384	4.5	55.3	1513
3	7.1	29.0	2071	7.7	33.9	1968	6.9	29.4	2409	5.4	54.2	1568
4	7.7	28.9	2048	7.2	33	1972	7.7	28.7	2422	6.1	49.7	1606
5	7.5	29.6	2076	7.4	32.8	1945	7.7	30.5	2372	5.9	49.2	1652
6	6.9	30.6	2075	7.3	32.7	1935	7.7	30.1	2348	5.5	48.6	1674
Average	7.4	28.4	2089	7.5	33.8	1878	7.2	29.9	2385	5.1	53	1573

*Sorptivity calculated from mass increase between 1 and 16minutes but not 1 and 64minutes as other samples due to non-linear relationship between mass change and the square root of time after 16minutes (Figure 9.16)

Table 9.6 – Measured sorptivity (S), porosity (P) and saturated density (D) for PC-PUM1 and PC-PUM2

Sample	PC-PUM1*						PC-PUM2					
	Structural			Lightweight			Structural			Lightweight		
Slice	S	P	D	S	P	D	S	P	D	S	P	D
1	6.4	15.7	2220	8.8	23	1707	7.2	20.3	2172	8.1	36.1	1368
2	7.4	14.7	2267	7.9	25.5	1772	8.6	20.0	2205	8.7	36.4	1579
3	7.2	14.3	2304	7.6	25.1	1775	7.7	20.2	2245	8.6	36.2	1635
4	7.7	14.5	2258	7.5	23.8	1825	7.7	21.5	2200	8.4	35.8	1693
5	7.6	15.9	2186	8.2	23.7	1882	8.1	20.0	2243	8.3	35.0	1739
6	7.5	17.4	2112	7.9	19.8	1948	7.5	20.6	2244	9.0	32.5	1803
Average	7.3	15.4	2225	8	23.4	1818	7.8	20.4	2218	8.5	35.3	1636

*Non- linear relationship between mass change and the square root of time (Figure 9.18)

Table 9.7 - Measured sorptivity (S), porosity (P) and saturated density (D) for PC-BB1 till 4

Sample	PC-BB1			PC-BB2			PC-BB3			PC-BB4		
	S	P	D	S	P	D	S	P	D	S	P	D
1	5.61	28.15	2295	4.59	34.29	2051	4.89	28.02	2291	4.49	29.92	2262
2	5.44	28.26	2311	5.71	27.23	2360	6.89	25.26	2404	5.85	25.12	2388
3	6.28	29.34	2022	4.52	33.08	2160	7.73	35.15	1676	6.90	26.21	2241
4	4.52	46.37	1351	6.42	29.58	2170	3.06	49.91	1248	5.22	43.80	1409
5	2.86	40.43	1131	4.05	50.28	1414	2.42	50.88	1212	2.45	52.81	1253
6	3.17	45.81	1242	2.39	54.17	1320	3.09	34.56	1016	2.25	53.89	1215
7	2.75	45.80	1176	2.09	54.33	1265	2.40	44.77	1142	2.03	51.54	1222
Average	4.38	37.74	-	4.25	40.42	-	4.36	38.36	-	4.17	40.47	-

The sorptivity and porosity differed depending on its composition, that is different results were gained for the structural and lightweight concrete layers. The sorptivity and porosity were also found depending on the amount of stratification and the materials being used. All these samples were cured under the same conditions.

9.2.1 *Structural and lightweight concrete sorptivity and porosity*

The porosity is significantly higher in the lightweight top layer than in the structural bottom layer when the variable density concrete is well stratified, Table 9.5 and Table 9.7. Whereas the change in mass with time increases faster in the lightweight concrete for samples PC-GB2 the opposite happens in samples PC-BB1 – 4. The sorptivity value of the lightweight concrete is however always lower (Figure 9.7) than for the structural concrete. The sorptivity (S) is gained by dividing the mass change (ΔM_t) by the difference of the saturated mass (M_{sat}) and the initial mass (M_0), which is high for a highly porous concrete:¹²

$$S = \frac{\Delta M_t}{t^{1/2}} \times \frac{d}{M_{sat} - M_0}; \quad \text{Where } d \text{ is the thickness of the slice and } t \text{ is time}$$

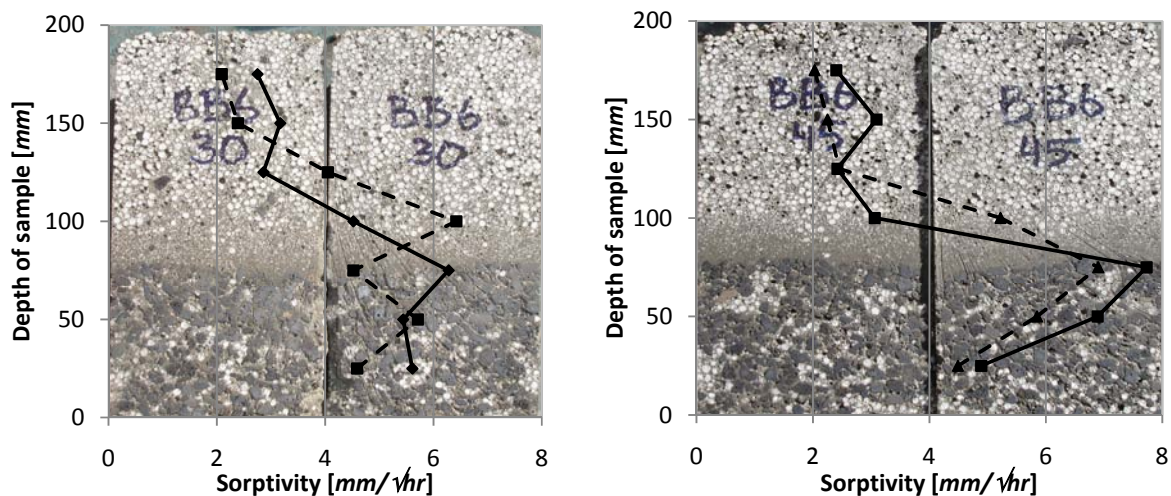


Figure 9.7 – Lower sorptivity is gained in the lightweight layer than in the structural layer

9.2.2 *Amount of stratification*

There are several factors that indicate the effect of stratification on the sorptivity of the variable density concrete:

- When the concrete is very well stratified, being a bit over vibrated, the paste started separating from the aggregates. The sorptivity increases on the boundaries between the structural and lightweight layer where the paste builds up, as can be seen in Figure 9.7
- The PC-GB1 cylinder was not properly stratified; the sorptivity values are therefore similar for the structural and lightweight cylinders being higher than experienced in the structural concrete from cylinder PC-GB2 which was well stratified
- When the cylinders are not well stratified the lightweight concrete seems to have higher sorptivity than the structural one, PC-GB1 in Table 9.5 and PC-PUM1 & 2 in Table 9.6

The sorptivity values for the structural and lightweight concrete layers do not change significantly once the concrete has stratified. That is, despite the central paste rich layer having higher sorptivity, the sorptivity of the lightweight and structural layer does not seem to change between the samples.

¹² Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999

9.2.3 *Different materials*

The variable density concrete containing pumice has the highest sorptivity and the lowest porosity whereas the concrete containing 2-4 and 0.5-1mm expanded glass beads has the lowest sorptivity. The difference in the mix design between the PC-GB and PC-BB samples is mainly that PC-GB contains perlite as fine lightweight aggregate whereas PC-BB contains 0.5-1mm expanded glass beads. The lightweight layer of PC-GB always absorbed more water than slices from the structural layer of PC-BB. Therefore there must be something in the material properties of the perlite causing it to absorb more water than the expanded glass beads. It must though be noticed that PC-GB and PC-BB slices are gained from different sample preparation as listed in Table 9.1.

Most of the well stratified samples had excellent absorption resistance as mentioned before. The structural layer of PC-GB2 had a slightly higher sorptivity value and therefore only providing good resistance to absorption. The general trend for the moderately stratified samples was to provide good absorption resistance but these also contained different materials. The porosity of the concrete was high, even for the structural concrete which contained significant amount of trapped lightweight material (Figure 9.3).

9.3 Surface finish



Figure 9.8 - Surface condition of panels after outdoor exposure

The surface finish was only examined visually which was fairly subjective as shown in Figure 9.9 and Figure 9.10.

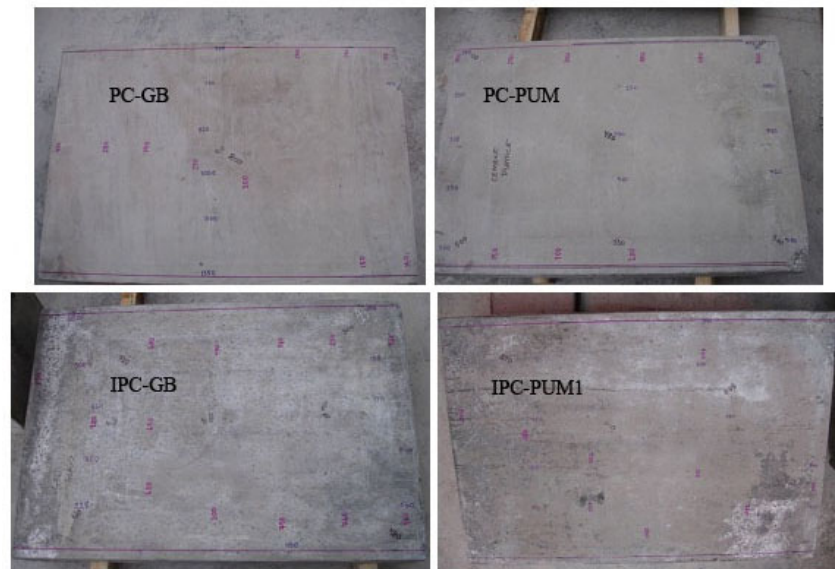


Figure 9.9 – Panels after being exposed at outdoor conditions for 5 months

Four panels (Figure 9.9) were cast to be exposed outdoors over 5 months during the Christchurch summer. These panels contained different materials, that is, Portland cement (PC), inorganic polymer cement (IPC), 2-4mm expanded glass beads (2-4 GB), pumice, perlite, slag and Greywacke chips (GW):

- PC-GB – containing PC, 2-4 GB, perlite and slag
 - The structural side was smooth, uniformly coloured with no visible cracks whereas the lightweight side was slightly friable and discoloured
- PC-PUM – containing PC, pumice, perlite and GW
 - The structural side was smooth, uniformly coloured with no visible cracks whereas the lightweight side was slightly discoloured but relatively smooth
- IPC-GB – containing IPC, 2-4mm GB, perlite and slag
 - The structural and lightweight sides were friable compared to the PC panels and discoloured due to chemicals appearing on the surface. This was mainly due to excess amount of chemicals and water used in the mix design
- IPC-PUM1 – containing IPC, pumice, perlite and GW
 - The structural and lightweight sides were friable compared to the PC panels and discoloured due to chemicals appearing on the surface. The lightweight layer was though not as friable as on the IPC-GB panel. Again the discolouring can be explained by excess chemicals



Figure 9.10 - Panels after being exposed at 35°C and 27% relative humidity for 80days

Four panels (Figure 9.10) were cast to be exposed at 35°C and 27% relative humidity for 80days. These panels contained different materials, that is, Portland cement (PC), inorganic polymer cement (IPC), 2-4mm expanded glass beads (2-4 GB), 0.5-1mm expanded glass beads (0.5-1 GB), pumice, slag and Greywacke chips (GW):

- PC-BB15 and 45 – containing PC, 2-4 GB, 0.5-1 GB and slag
 - The structural side was smooth, uniformly coloured with no visible cracks whereas the lightweight side was slightly friable and discoloured
- IPC-BB – containing IPC, 2-4mm GB, 0.5-1 GB and slag
 - The structural and lightweight sides were friable compared to the PC panels and discoloured due to excess chemicals appearing on the surface. These did have a better finish than the other IPC panels but the paste could though still be easily scraped off
- IPC-PUM2 – containing IPC, pumice, 0.5-1 GB and GW
 - The structural and lightweight sides were friable and the concrete was weak and tended to break on the corners. It was also discoloured due to excess chemicals appearing on the surface

The surface finish of the variable density concrete panels made from Portland cement (PC) is better than for the inorganic polymer (IPC) panels. The poor finish observed on the IPC panels is related to excessive water and chemicals in the mix design, but the paste could easily be scraped off. The surface of the PC panels was dense and no cracks were observed visually after exposure.

Excessive vibration can cause the lightweight material at the top of the panel to start losing paste, leaving the surface rough or friable and easily scraped off.



Figure 9.11 – Excessive vibration causes lightweight material to lose paste

9.4 Conclusion

Variable density concrete was found to have poor permeability, both in the structural and lightweight layer. OPI values from the structural layer were similar to the ones measured in the lightweight layer, due to a significant amount of trapped lightweight material within the structural layer. The OPI value was also found to depend on the amount of stratification. Over vibrated samples had slightly lower OPI values in the structural and lightweight layers and were less impermeable between the two layers. As the structural layer includes steel mesh, the low OPI values indicate a 20mm cover depth in the half scale panels being insufficient but a 30-40mm cover depth on a full scale panel being adequate. This backs up the New Zealand Standard¹³ (NZS 3101), which has a minimum cover requirement of 25mm for 25MPa concrete in the estimated environment of the variable density panel.¹⁴ The lower limit of strength for the structural concrete was initially 25MPa but the strength was found to be lower, as discussed in chapter 6.

The concrete was classified as a concrete with good to excellent absorption resistance but highly porous, where the structural layer has high porosity due to trapped lightweight material. The lightweight layer was found to have lower sorptivity but higher porosity than the structural layer. The sorptivity and porosity were also depended on the amount of stratification and the materials being used. Mixes containing pumice had higher sorptivity and lower porosity than the other mix designs. Mixes containing two grades of expanded glass beads had lower sorptivity than mixes containing perlite as fine lightweight aggregate material, indicating that the material properties of perlite causes the concrete to absorb more water.

Because the concrete has poor permeability, is highly porous and if it has been over vibrated, a rough surface finish, it is recommended the lightweight concrete has a surface coating. The permeability of the structural layer and the NZS3101 indicate that the concrete cover should be not less than 25mm. Delamination of the variable density panel was not assessed in this research but is a likely mode of durability failure in the panels.

¹³ NZS 3101:2006

¹⁴ NZS 3101:2006

9.5 References

- Alexander, M.G.; Mackechnie, J.R. and Ballim, Y. 1999. “*Guide to the use of durability indexes for achieving durability in concrete structures.*” Departments of Civil Engineering University of Cape Town, Cape Town, South Africa.
- Ballim, Y. 1991. “*A low cost falling head permeameters for measuring concrete gas permeability.*” Concrete Beton 61:13-18.
- Ballim, Y. 1993. “*Curing and the durability of OPC, fly ash and blast-furnace slag concretes.*” Materials and Structures 26(158):238-244.
- Beushausen. H.D.; Alexander M.G. & Mackechnie, J.R. 2003. “Concrete durability specifications in an international context” Betonwerk + Fertigteil-Technik, Concrete Plant + Precast Technology 7:22-32.
- Kelham, S. 1988. “*A water absorption test for concrete.*” Magazine of Concrete Research 40(143):106-110.
- Mackechnie, J.R. 2006. Lecture notes in ENCI 426, *Concrete Structures*, first semester. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R. 2007. Unpublished Research findings, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
- New Zealand Standards. 2006. *NZS 3101: Part 1:2006, Concrete Structures Standard. Part 1 – The Design of Concrete Structures.* NZS, New Zealand Standard.
- Nilsson, Lars-Olof. 2003. Durability concept; pore structure and transport processes in John Newman (Ed.), *Advanced Concrete Technology*, Butterworth-Heinemann, England.

9.6 Appendix

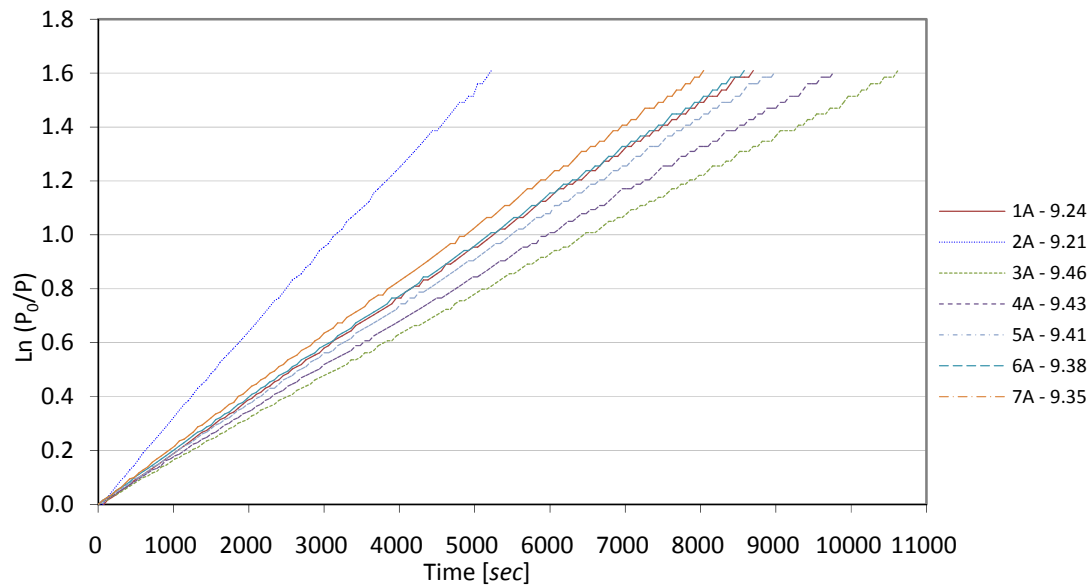


Figure 9.12 – Oxygen permeability testing results for PC-BB1

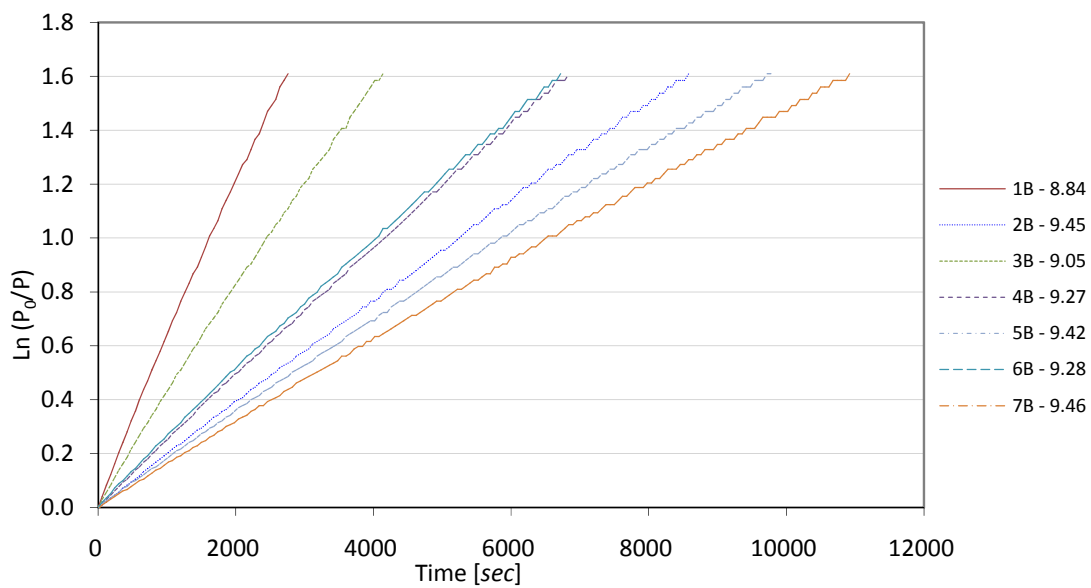


Figure 9.13 – Oxygen permeability testing results for PC-BB2

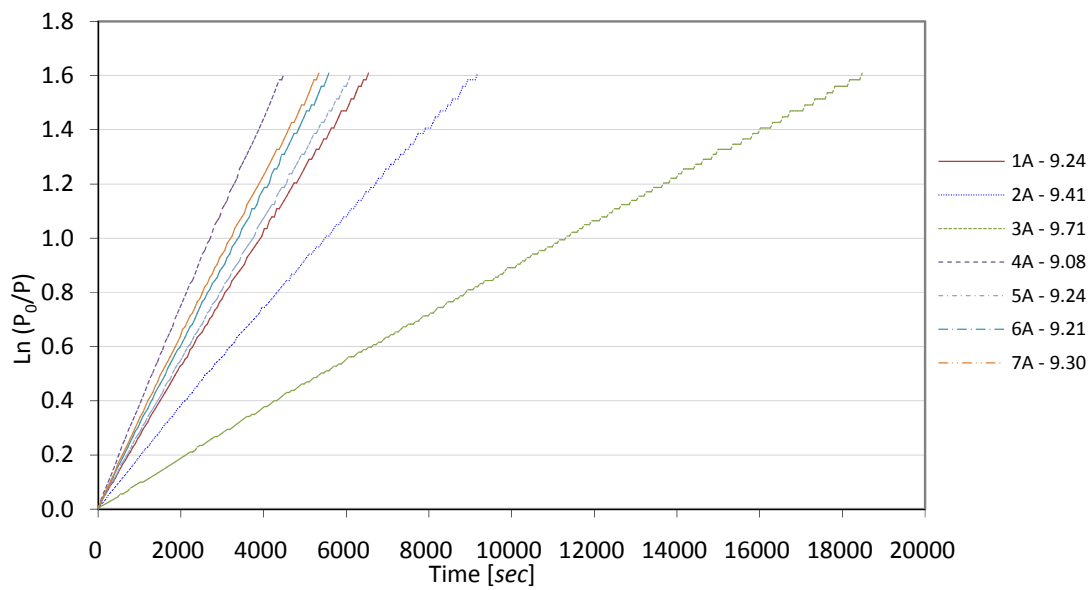


Figure 9.14 – Oxygen permeability testing results for PC-BB3

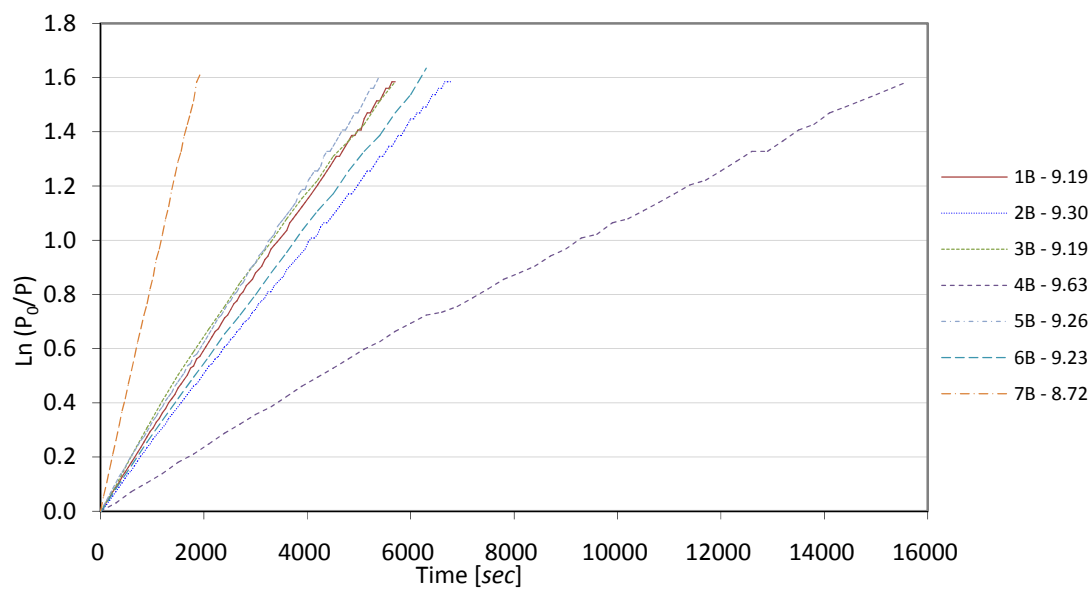


Figure 9.15 – Oxygen permeability testing results for PC-BB4

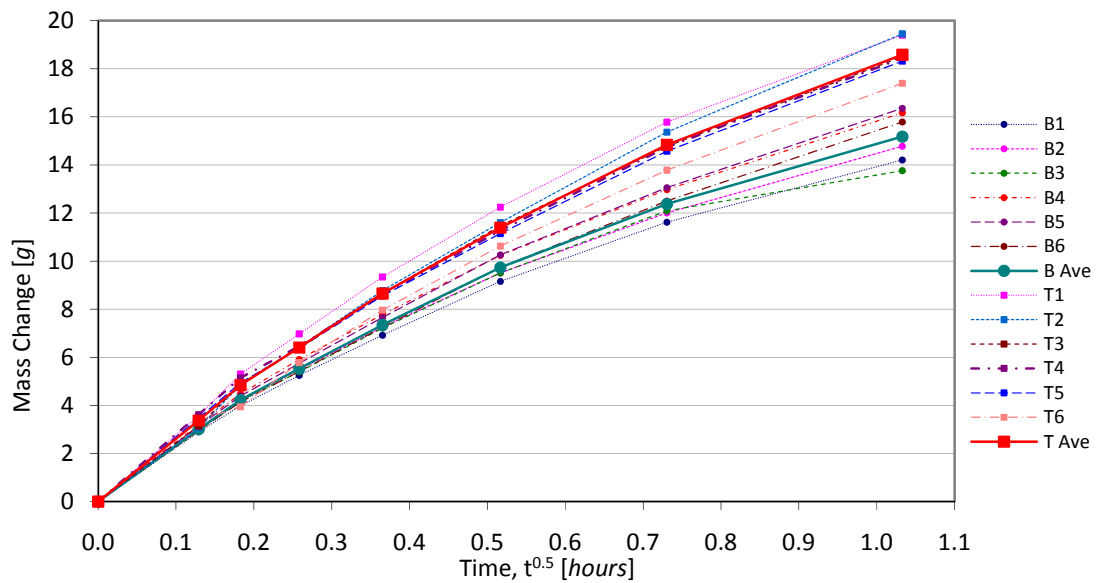


Figure 9.16 – Results of water sorptivity measurement of PC-GB1 samples

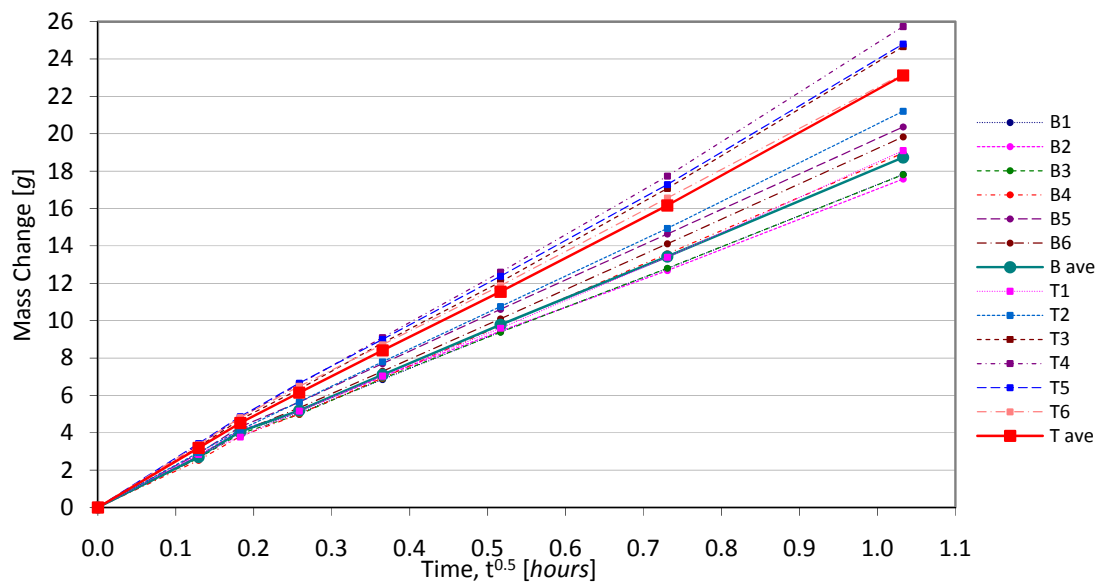


Figure 9.17 - Results of water sorptivity measurement of PC-GB2 samples

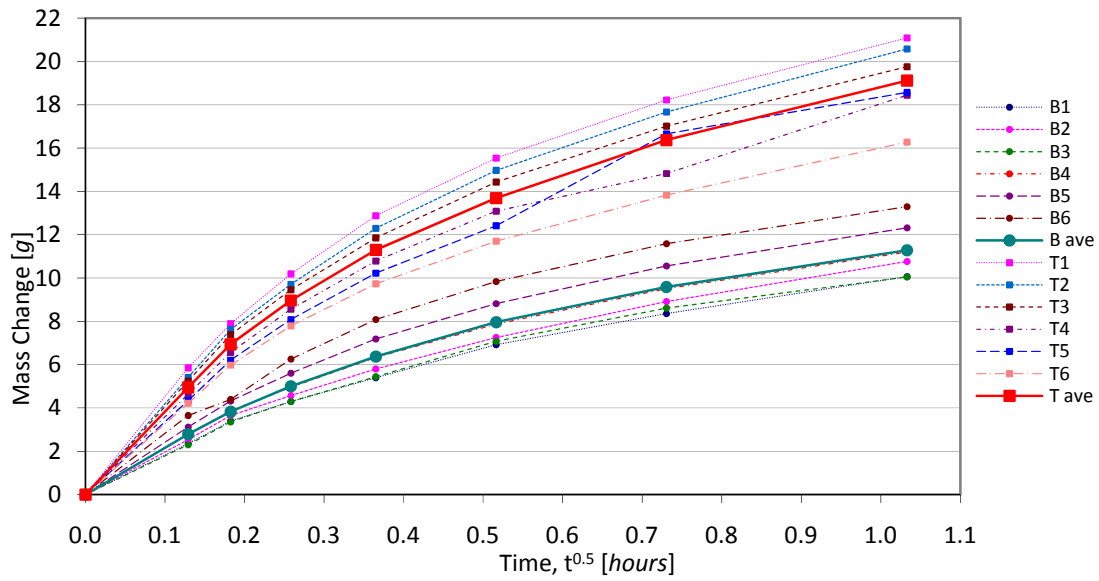


Figure 9.18 - Results of water sorptivity measurement of PC-PUM1 samples

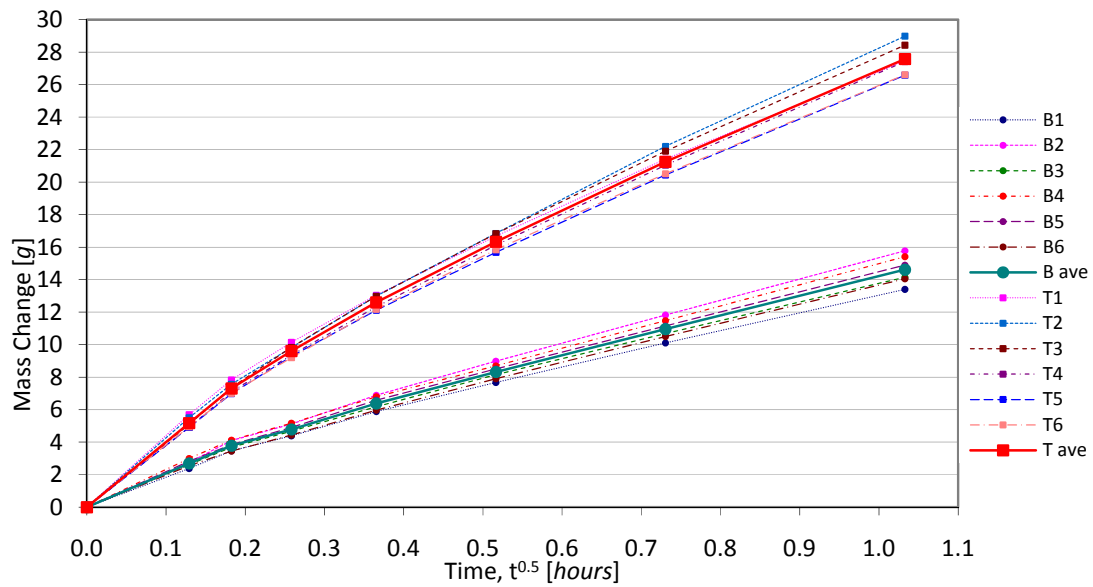


Figure 9.19 – Results of water sorptivity measurement of PC-PUM2 samples

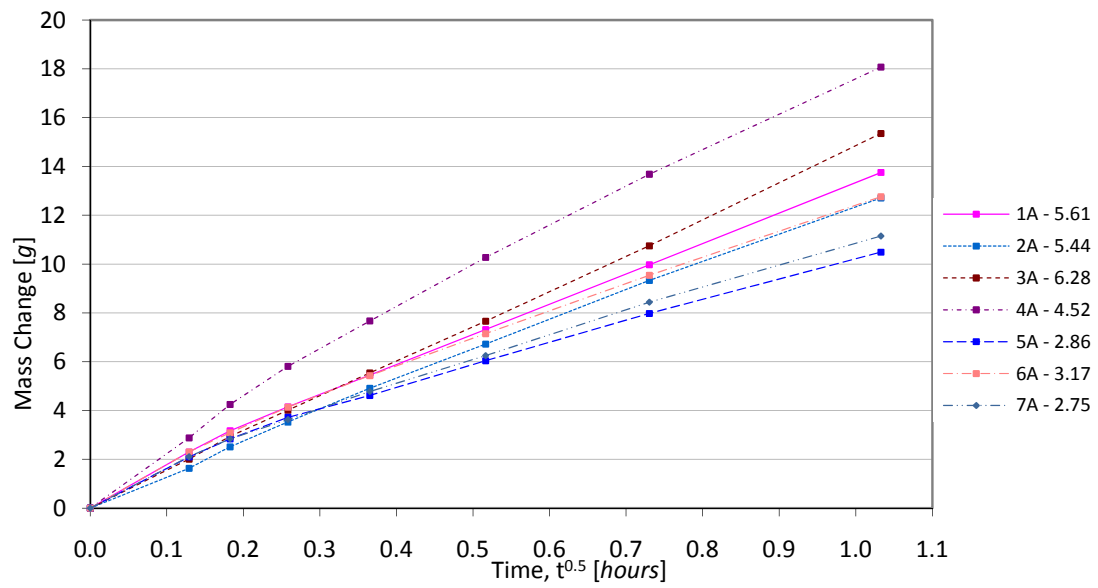


Figure 9.20 - Results of water sorptivity measurement of PC-BB1 samples

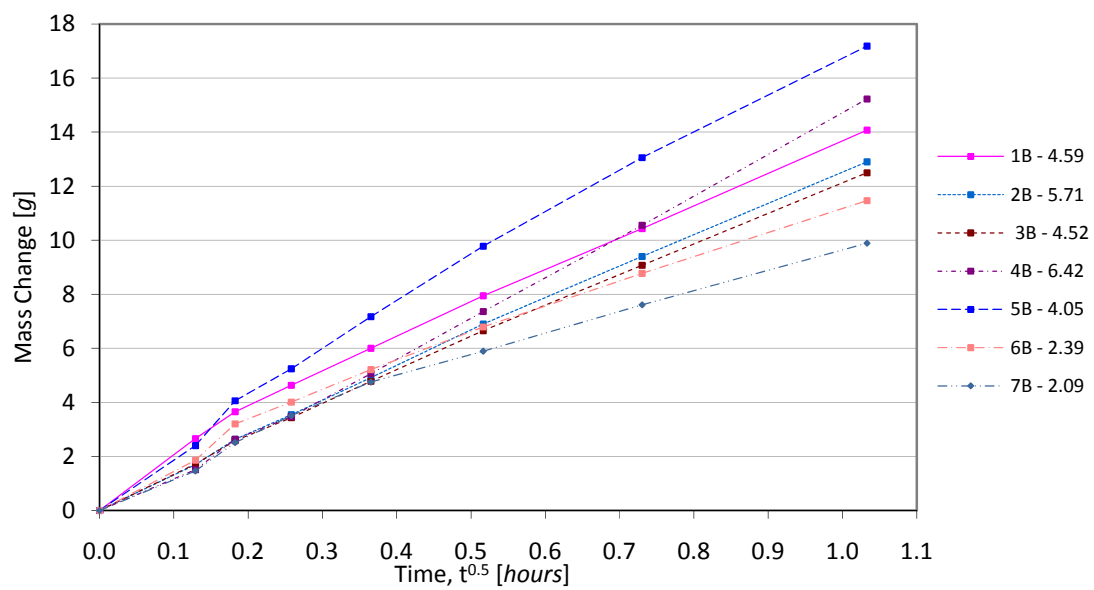


Figure 9.21 - Results of water sorptivity measurement of PC-BB2 samples

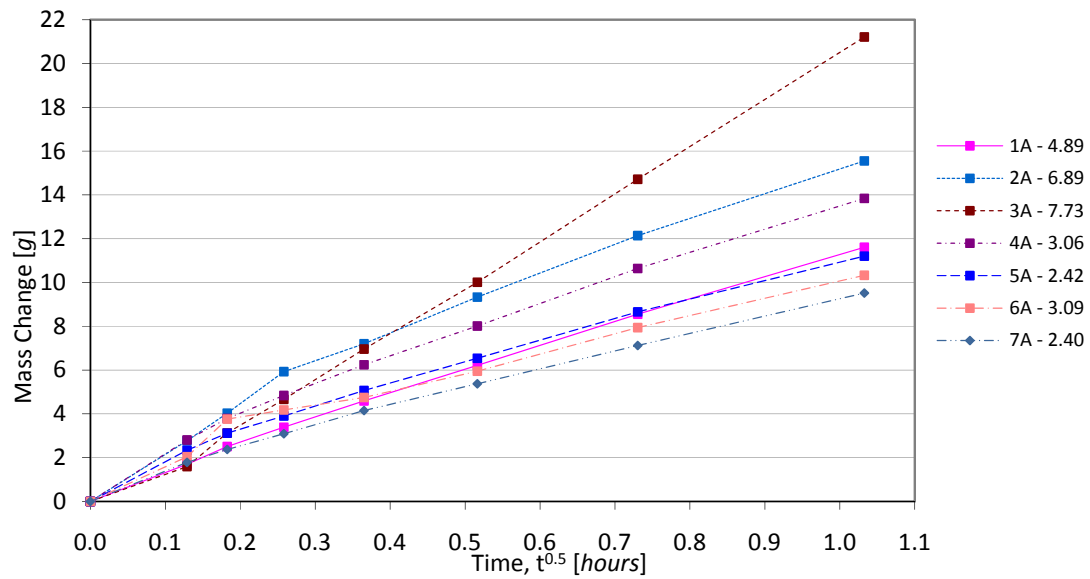


Figure 9.22 - Results of water sorptivity measurement of PC-BB3 samples

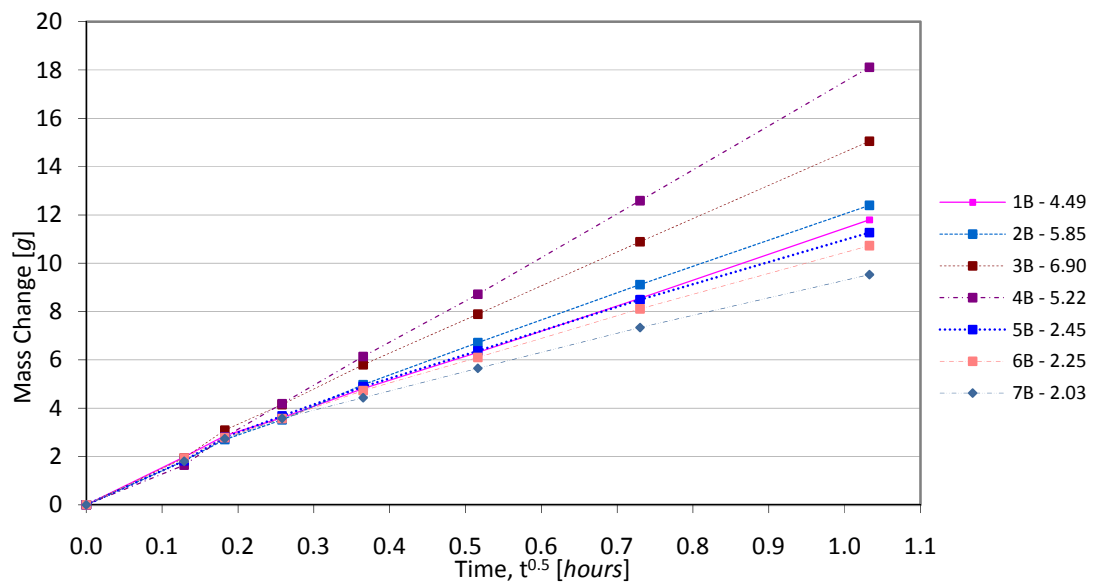


Figure 9.23 - Results of water sorptivity measurement of PC-BB4 sample

10 Conclusion & Recommendations

The structural performance, serviceability (e.g. warping and cracking) and durability had to be assessed, modelled or measured by experiment for the variable density concrete panels. The initial aim of this research was therefore to:

- Assess the structural performance of reinforced concrete panels in the laboratory under typical loads likely during handling and after installation
- Model and measure the serviceability of typical panels in terms of warping, cracking and shrinkage
- Cast and monitor trial walling systems on site exposed to outdoor weather conditions
- Assess the durability performance of the material

On top of these initial goals some further mix design trials had to be carried out where the fresh properties of the variable density concrete were assessed and the degree of stratification of the concrete measured after vibration.

10.1 Conclusion

Fresh properties

When assessing the fresh properties it was hoped that the slump flow would give an indication of the stratification potential. For the concrete to be able to stratify it had to have a slump flow within a defined range, but stratification could not be guaranteed. Rheology provided a better indication of the stratification potential, as defined rheological ranges were found to indicate the stratification potential. The yield shear stress and the plastic viscosity had to be relatively low to provide concrete that was flowable enough to allow proper stratification. To gain good stratification, lower plastic viscosity allowed higher yield shear stress and vice versa.

Stratification

The degree of stratification was found to depend on the intensity and time of vibration. These factors were optimised for various mix designs, as it was highly related to the aggregate and binder materials being used. The quality of the outer surface and the interface between the structural and insulating layer were affected by excessive vibration whereas restricted vibration led to poor stratification of the mix.

In the fresh state a method measuring the penetration depth was developed to estimate the amount of stratification with limited success, but only one type of rod was used leaving some potential to modify the method. In the hardened state a stratification coefficient was calculated by finding the centre of mass of stratified cylinders which gave a good indication of the degree of stratification. This method provides a definitive measure of stratification in the hardened state but is not suitable as a control test during production.

Hardened properties

The structural concrete was found to be stronger, stiffer and heavier than the lightweight concrete, but the difference depended on the materials being used. The lightweight concrete was generally heavier and stronger than what was aimed for initially whereas the structural concrete was lighter and weaker.

Testing of strips cut from panels produced reasonable performance having an adequate strength capacity for likely service conditions but the strength required to withstand handling loads at early ages has not been assessed. The strips did not show any signs of buckling but generally failed at the interface between the structural and lightweight layers.

The strength of the variable density concrete was found to be affected by several factors:

- **Relative strength of the layers** – stronger layers provided stronger panels
- **Degree of stratification** – the strength decreased as the stratification increased
- **Curing environment** – more severe drying decreased the strength
- **Relative thickness of the structural layers** – increased thickness of the structural layer increased the strength
- **Amount of defects such as compaction voids and contamination** – trapped lightweight material reduced the strength of the structural layer

Serviceability performance

Drying shrinkage of the lightweight concrete was typically twice that measured in the structural concrete but the amount of shrinkage depended on the materials and mix design being used. As warping is mainly due to differential shrinkage within a member, the variable density panel was expected to warp significantly. The difference in deflection however never exceeded 0.2% indicating that warping would not significantly affect the serviceability of the panels. A deflection within a member is generally accepted if it is less than 0.2%.

The amount of warping was related to the degree of stratification. The amount of warping decreased with better stratification as more stress and strain relief occurred in the lightweight concrete when not interfered with stronger particles. The lightweight concrete is significantly weaker as well as being less stiff than the structural concrete that it creeps to follow the structural concrete layer. As strength of the lightweight concrete got closer to the strength of the structural, concrete the samples were more prone to warp as the lightweight concrete provided more resistance in following the deformation of the structural concrete.

Other factors affecting the amount of warping were:

- **Curing environment** – more severe drying increased the warping
- **Drying shrinkage** – decreased drying shrinkage decreased the amount of warping
- **Measuring time** – longer measuring time gave higher amount of warping, but the increase in warping decreased with time

Thermal properties

The thermal conductivity and the specific heat were significantly lower in the lightweight insulating concrete layer than in the structural thermal storage layer. The initial objectives were generally not reached and further development is required to improve thermal performance.

Factors found affecting the thermal conductivity and thereby the R-value were:

- Moisture content reductions caused a decrease in thermal conductivity
- Increased cement hydration increased thermal conductivity
- Lower density reduced thermal conductivity
- Improved stratification increased the overall R-value

- Inorganic polymer concretes had lower thermal conductivity than Portland cement concretes

Durability

Variable density concrete was found to have poor permeability, both in the structural and lightweight layer as significant amount of trapped lightweight material was within the structural layer. The low OPI values indicated a 20mm cover to reinforcement on the half scale panels was insufficient, as well as the New Zealand Standard¹ (NZS 3101) which requires a minimum cover of 25mm for a 25MPa concrete. On a full scale panel the proposed cover is 30-40mm which is adequate.

Variable density concrete was classified as concrete with good to excellent absorption resistance. It was however found to be highly porous, where the structural concrete had trapped lightweight material. The lightweight concrete was found having lower sorptivity but higher porosity than the structural concrete.

Surface coating on the lightweight concrete would be recommended as it has poor permeability properties as well as being highly porous and if it is over vibrated it may have a rough surface finish. Delamination of the variable density panel was not assessed in this research but is a likely mode of durability failure.

10.2 Potential for variable density panel

Research shows promising potential of producing variable density concrete panels. These panels can be manufactured with simple and energy efficient processes. The stratified concrete was easily made in laboratory conditions but development needs to move from the laboratory to a precast concrete plant to assess the practical feasibility. The panels were found to have relatively good thermal properties and suitable for moderate climates such as the Mediterranean. Most of the major technical concerns were proved to be not as severe as first thought.

Controlling the segregation – the concrete was found to remain fairly homogenous during mixing and handling but stratified under moderate levels of vibration if correctly designed.

Potential of warping – if the concrete was properly stratified the warping was found insignificant, as the stresses were relieved in the lightweight layer by creep.

Providing sufficient strength without excessively compromising the thermal performance – the concrete had an adequate strength capacity for likely service loads and further improvements to strength are likely to compromise thermal performance.

Ensure sufficient durability to provide satisfactory long-term service – the concrete had good to excellent absorption resistance, poor permeability properties and was highly porous. Delamination has not been assessed but is a likely mode of durability failure in the panels.

Achieving a satisfactory surface finish – if the concrete was not over vibrated, a reasonable concrete finish was observed requiring minimum treatment on site

Providing a robust enough mix design – by using consistent aggregate materials, a good consistency in the fresh properties was also experienced

¹ NZS 3101:2006

As the concrete had poor permeability properties, was highly porous and has a poor finish if over vibrated, a surface coat placed on the lightweight concrete would be recommended. The permeability results also indicate that the minimum concrete cover should be 25mm but that is also required by the New Zealand standard, as the structural concrete strength is at the lower limits of what was aimed for.

10.3 Recommendations for future research

As the variable density concrete is a new concept there are many aspects that need to be investigated, but not all of these could be covered in this research:

- Casting and testing of the variable density concrete needs to move away from the laboratory to the precast yard where some full scale panels can be cast
- The structural performance needs to be tested on full scale samples, and better control tests need to be developed as the structural and lightweight cylinders did not indicate the final strength of the variable density concrete strips cast
- Two methods to assess the stratification in the fresh state were mentioned, measuring the penetration depth and a wet sieving method, but these tests were not feasible. These methods need to be modified or a new test method needs to be developed
- The mix design needs to be optimised for thermal performance to produce R-values above $1.0m^2K/W$
- The durability of the variable density concrete needs further investigation as only a brief study was performed in this research
- Delamination of the variable density panel was not assessed in this research but is a likely mode of durability failure and probably one of the most critical issues of the panels

10.4 References

- New Zealand Standards. 2006. *NZS 3101: Part 1:2006, Concrete Structures Standard. Part 1 – The Design of Concrete Structures*. NZS, New Zealand Standard.